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Higher Resolution Model Forecasts of an East Coast Storm

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Introduction

There is increasing evidence that the key to early improvements in operational numerical weather prediction is the reduction of truncation error, which occurs when finite differences are used to approximate derivatives in the basic meteorological equations.

This error can be reduced by decreasing the distance between gird points, or by estimating derivatives from more than two gridpoints (e. g. "fourth order differencing") or by spectral methods of integration, i. e. expressing the equations in terms of amplitudes of spherical harmonics. NMC is pursuing all three, but the value of reduced grid-point spacing has already been demonstrated on a regional basis by the LFM and has now been programmed for a hemispheric model for comparative testing.

Figure 1, taken from NMC Office Note 144 (1), shows the superiority of the LFM over the coarser mesh operational 6L PE model, averaged over twelve months, December 1975 through November 1976. The average skill scores, however, do not reveal the outstanding improvements made on infrequent cases of storm development and smaller scales generally.

Experience with an even finer mesh limited area model, the Movable Fine Mesh (MFM) model, which was designed by Dr. John Hovermale of NMC, primarily to forecast hurricane tracks with a moving grid, has shown that improved forecasting of precipitation can be achieved when its very fine mesh calculation grid is used in a stationary mode over continental areas.

Historically, spectral analysis has been used to initiate the MFM runs. Recently, the MFM was programmed to run from LFM initial analyses as well, Tests showed that on some occasions the two initial states produced considerably different forecasts and that the LFM regional analysis provides more accurate input to the MFM than does the spectral analysis. Recently, a series of four test cases were run on significant precipitation events in the fall and winter seasons, and threat scores for the half-inch isohyet (12-hour accumulation) were calculated from the 6L, PE and LFM as well as the MFM. The results are shown in the following table reported by Dr. Hovermale in the last quarterly Numerical Prediction report of NMC.

AVERAGE THREAT SCORES AND BIAS FOR 0.5" ISOHYET,
FOUR FALL-WINTER PRECIPITATION FORECASTS
12-HOUR ACCUMULATED AMOUNTS

	THREAT SCORES		
	24	36	48
6L PE	.34	.14	.02
LFM	.32	.25	.03
MFM	.52	.36	.30
	BIAS		
6L PE	.97	1.14	2.81
LFM	.79	1.57	3.07
MFM	1.25	1.77	2.00

It should be emphasized that these scores do not imply that the MFM is always that accurate. Its performance during convective summer situations and over mountainous areas of the western United States is known to be poorer. While Dr. Hovermale and his staff attribute the improvement largely to the use of the LFM analysis, they do not rule out a contribution from the use of more accurate LFM boundary values in place of the coarse mesh P.E.

Finer Mesh Hemispheric Models:

The Development Division of NMC has been working for some time on a number of finer resolution hemispheric models as candidates for replacement of the current operational coarse mesh 6-L hemispheric P.E. model. The main problems has been how to reduce the greatly increased running time of the finer mesh models when calculated on a hemispheric basis. The two most practical current methods for operationally reducing running times are spectral methods of integration and pressure gradient time-averaging for grid point calculation models. Time-averaging of the pressure gradient terms in the equations of motion had been used in the coarse mesh operational P.E. model a few years ago to shorten the running time on the slower CDC 6600 computer by increasing the time steps from 10 minutes to 20 minutes. The longer time step was not needed when the faster 360-195's replaced the 6600's, so pressure gradient averaging was not programmed into the coarse mesh 6-L PE model when it was recoded for the 360-195 computer. Now this has been accomplished for a fine mesh version of the 6-L PE model, which would enable it to be run operationally on the 360-195's, although it will still take about 30 minutes longer than the coarse mesh for a 48-hour forecast. In addition to the hemispheric fine mesh model (HFM), two other hemisphere models are in contention for replacement of the coarse mesh operational model:

A Nested Grid Model (NGM) being developed by Dr. Norman Phillips of NMC. The NGM has a nested finer mesh grid covering about a quarter of the hemisphere from near Japan across North America to the coast of Europe with half the mesh length of the hemispheric grid. This model also has the capability of a second even finer mesh grid covering an area about the size of North America nested within the fine mesh grid (NGM 3). This model has 10 layers of vertical resolution but does not yet have some features the other models have, such as radiation, and heating and evaporation from oceans.

The third hemispheric model in contention is Dr. Stackpole's 9-Layer (9-L) model, which uses latitude-longitude gridpoints with a resolution of 2° latitude.

These models were all run on 7 selected forecast situations over the last two years to determine which model would be evaluated in a further series of tests against the coarse mesh hemispheric model. These forecasts were all run from the same initial analyses, viz. the global final spectral analyses.

The forecasts were evaluated by statistical scores and by a 5-man jury of forecasters from the Forecast Division at NMC. The subjective evaluations of the forecast fields at various levels out to 84 hours, identified only by coded designations, and scrambled so that the jury would not know which model was which, were in close agreement with the statistical results. It turned out that both the hemispheric fine mesh model forecasts and the nested grid model forecasts both improved over the coarse mesh operational 6-L P.E. model forecasts. One of the selected cases based on initial analyses at 00Z Jan. 9, 1977, involved the development of a Northeast storm. This case will be discussed in the next section, showing the results from the four hemispheric models, i.e. the 6LPE, HFM, 9-L, NGM, as well as the very fine mesh version of the NGM, referred to in this paper as the NGM(3). In addition, the forecasts made by two limited area models from the same initial data will be shown. The LFM forecast was the regular operational forecast made from the Cressman (gridpoint) fine-mesh analysis (sometimes referred to as the 2-dot analysis), which uses first guesses and boundary values from the coarse mesh forecast made 12 hours earlier. The MFM precipitation forecast used the current LFM fine-mesh analysis and LFM boundary values rather than the customary coarse mesh PE boundary values. The MFM circulation forecasts are not shown but only the precipitation forecasts.

The Northeast Storm of January 11, 1977

The northeast storm of January 11, 1977, grew out of a disturbance which was located at initial time 00Z Jan. 9, 1977, in northern Mexico near the big bend in the Rio Grande. This Low moved across the South during the next 24 hours to near Nashville, TN at 00Z Jan. 10, shown in fig. 2, with a suggestion of a secondary center in Alabama. During the next 24 hours, the Nashville center moved northward to southern Ontario, while a secondary developed near the Maryland coast at 12Z Jan. 10 and deepened rapidly to become the main storm center by 00Z Jan. 11 near Portland, MA, 48 hours after initial data time. This storm moved northward through Quebec to Fort Chimo on 12Z Jan. 12, 84 hrs. after initial data time.

The 24-Hour Model Forecasts

Figure 3A shows the predicted 24-hour surface progs. The HFM, and the NGM and the PE are practically identical in positioning the low center over Alabama. None, however, are very close to the observed Low center near Nashville, which has a thickness of about 5460 m. The model predicted centers show a 5580 thickness for the HFM and the PE, which is right on the observed value, while the NGM has a 5640 value which is 60 m. too warm.

Since none predicted the colder center near Nashville, it would seem that the models are basically forecasting a secondary at the peak of the warm sector.

Figure 3B shows the 24-hour forecast made from NGM-3 grid model. It was virtually identical to the 2-grid model. The operational 24-hour LFM in fig. 3B is a bit north of the position of the hemispheric models with accurate thicknesses. The 9-L is too far back and 60 m. too warm at its predicted location.

All models are good on the rain-snow thickness zone except the NGM is too far south over Virginia, whereas, the observed was near the PA border.

At 500 mb there are 3 very important vorticity centers at initial time on 00Z Jan. 9, 1977. A 22+ center near Lake Athabaska in Canada is plunging southeastward heading toward the Dakotas, and another center (18+) near Salt Lake is moving southeastward toward west Texas, while a third center near El Paso is located in a southwesterly flow and is headed northeastward.

Figure 4A and 4B show the verifying locations of the vorticity centers at 500 mb, together with the model predictions. The Canadian center has moved to North Dakota and the Salt Lake center has moved to north Texas, with an extension northeastward toward Ohio presumably containing the remains of the 24-hr. earlier El Paso center. The PE prediction maintains the two southern centers, with the western center too far west. The HFM vorticity center is in better agreement with the observed, while the NGM is too far back like the PE. Fig. 4B shows the 9-L about the same location as the HFM but weaker. The LFM is much farther south than the others in line with its propensity for excessive digging in troughs. There is a distinct difference between the NGM-3 and the NGM-2. The NGM-3 develops a strong center near Memphis with no change at sea level, while still keeping one over New Mexico as in the 2-grid version but still has no extension toward Ohio as observed. Thus, the 3-grid NGM is no improvement.

Looking at the 24-hr. predicted precipitation patterns, figs. 5A & 5B, note the extensive area which occurred in the East and South. About 2 inches of rain occurred in northern Alabama just north of the warm front, while another maximum of 0.86" occurred in heavy snow in northwest Tennessee and southeast Missouri. The HFM gave probably the best prediction with a max of 1.76" and overall average. The LFM with 1.22 was next best. The NGM-2 was next best with 1.20" max but too far south and the 0.5" line was too far east across the Georgia coast. The PE was good in position but the max of 1.08" was not as good as the others and axis extending northward to Kentucky was not as good as the HFM. The 9-L was too far back. The MFM (fig. 5C) was an improvement over the LFM by extending the precip farther north in the Midwest but the extension eastward to the Georgia coast was in error. None of the models forecast the second maximum near the boot heel of Missouri. Nevertheless, a good snow forecast could be made from any of these models except the 9-L.

Looking quickly at 300 mb., figs. 6A & 6B, there is a 150 KT isotach over Louisiana with a SW-NE direction. The PE certainly verifies best on this feature with 150 KTS forecast. All the others predict winds too weak or in less accurate position. The HFM is second best. The 3-grid NGM doesn't improve the 2-grid. The PE, however, is too strong on the northerly jet max over the Rockies. The HFM and NGM forecasts are both better.

The 48-Hour Forecasts v.t. 00Z Jan. 11, 1977

The 48-hr. surface forecasts showed a large dispersion of surface centers compared with the small clustering at 24 hours, see fig. 7A. All the models seemed to be predicting the coastal storm, although some of the predictions were a little too far inland. Again, none predicted the major center farther inland that moved across Ohio.

The HFM again made the best prediction (fig. 8A) in terms of central pressure 986mb. and proximity to the observed position near Portland, ME. This was a great improvement over the PE, which was too slow and shallow, and also an improvement over the LFM, which was too deep and about 12 hrs. too slow.

The NGM (both versions) was much too slow (near Norfolk) and the 9-L (fig. 8B) was too far to sea, too weak, and left a spuriour secondary too deep near Charleston, S.C.

The 5400 thickness line was observed thru the storm center near Portland. The HFM was too warm by 60m. (5460 m) as was the LFM, and the PE was 120 meters warmer while the NGM was 180 m. too warm. Being too slow and west of the observed coastal track (except the NGM and 9-L) they would have been even warmer and called for less snow in transitional areas. This is consistent with Grossman's findings reported in the Tech. Attachment to the Nov.-Dec. 1976 NMC Newsletter, that in the eastern U.S. the LFM forecasts thicknesses too warm on the average where heavy snow occurs. The only model with cool enough thicknesses in the Northeast was the 9-L but it was associated with a surface circulation that bore little resemblance to the observed.

The 500 mb analysis at 00Z Jan. 11, which verified the 48 forecasts, had a deep Low center 5060 m. near Toronto and a 24-vort. center over Pennsylvania, the result of the Texas and North Dakota centers 24 hours earlier combining.

The PE model 48-hr. prediction (fig. 9A) suffered from a severe locked-in vorticity center over Mississippi, plus two centers near the Lakes Region. The HFM was a decided improvement showing only one center over eastern TN. The NGM had a bad locked-in 14 vorticity line over southern Alabama, and anticyclonic curvature of vorticity lines over southern New England which was very poor. The NGM 3 (fig. 9B) improved substantially over the NGM pulling the vort. center to Kentucky somewhat better than the HFM, but the NGM 3 has a bad anticyclonically curved strong gradient of vorticity lines near the mid-Atlantic states.

The LFM on the other hand had too much cyclonic vorticity in the TN-VA region. The LFM was also much too deep in TN by as much as 300 meters, far deeper than any of the other models. None of the models forecast the closed contour Low at 500 mb near Toronto.

The 9-L forecast a very poor vorticity pattern with a weak center over PA near the location of the observed center and another deeper center over KY. This pattern was similar to NGM-3 with a spuriour vorticity ridge over NC but with weaker gradient than the NGM-3.

On balance the HFM pattern appeared best of the models, although it alone among the models, predicted a semi-cutoff cyclonic vorticity center near Brownsville, TX, which was erroneous.

Looking at the 48-hr. precipitation pattern, the main features of the verifying pattern were a 3.00" maximum near Portland, ME, associated with the main coastal storm center, and another maximum 1.00" isohyet over southern Ontario associated with the almost disappeared surface Low in that location, and with 500 mb. Low centered there.

The PE model was very poor (fig. 10A) with one maximum of 0.82" near the mid-Atlantic coast and another maximum of 1.17" over Georgia associated with the spurious vort. center over Mississippi.

The MFM (fig. 10C) gave the best overall pattern with a 2.00" isohyet into CT and the best clearing pattern in the southeast U.S. The LFM was poorer than the MFM with a maximum isohyet of 2.5" too far south near the MD coast. The best hemispheric model forecast was given by the HFM with a 2.00" isohyet near western MA. It, however, predicted a spuriour 1.00" isohyet near Brownsville associated with the bogus vorticity center there.

The 9-L forecast (fig. 10B) was also good with a 1.50" isohyet in southern New England, but did not seem to have any relation to the circulation pattern. It was also poor in the Great Lakes. The NGM forecasts were very poor. None of the models predicted the 1.00" of precip (all snow) over southern Ontario.

At 300 mb. the 48-hr. observed winds showed a 150 isotach along the Carolina coast. The PE model (fig. 11A) verified best with a 130 KT isotach over NC. The HFM was relatively poor showing a 150 KT isotach too far south near the GA coast. The NGM models were second to the PE in positioning the 110 KT isotach but the winds were not strong enough. The 9-L (fig. 11B) was poorest with winds too weak in the southeast, and a spuriour isotach maximum north of New England.

The 84-Hour Forecast v.t. 12Z Jan. 12, 1977

The HFM (fig. 12A) did not improve on the 6 L PE forecast of the storm center over northern Quebec, but improved considerably on the PE in the position of the pressure pattern and trough near Newfoundland and over the western Atlantic.

The NGM was poor in positioning the storm Low too far east near New Brunswick, but predicted a beautiful pressure pattern off the Atlantic coast. The NGM-3 improved on the NGM by positioning the storm center farther northwest toward Hudson Bay and deepening the center.

Both the PE and HFM predicted spurious Lows over southern Texas. The HFM was not as bad as the PE. Both NGM's were best over the South. The 9-L (fig. 12B) was probably the poorest model at 84 hrs. On balance the HFM appeared best.

At 500 mb. all models forecast the Low center over Canada to the south and west of the observed center (figs. 13A and 13B). All showed vort. centers too far west of one observed center near Newfoundland, but the HFM and NGM 3 had the best phasing. The HFM forecast the best position for the northern center over Quebec.

A secondary vorticity center observed near Detroit was best forecast by the PE model, while the NGM and HFM models forecast this center too far to the northwest near Lake Superior. However, the PE, the 9L and the NGM-3 models forecast erroneously deep vorticity troughs southeastward toward the Atlantic coast.

Looking at the 84-hr. precipitation pattern (figs. 14A and 14B), the main features were scattered .01" isohyets in the Great Lakes, the northeastern states and southern TX.

The HFM was best in clearing the precip probability associated with the Quebec storm out of ME, whereas, the coarse mesh PE and the 9-L both showed the western edge of that precipitation area still over ME. Both the NGM's were poor in greatly overforecasting the precipitation over a large area in the East and Midwest.

The NGM did forecast some of the observed south Texas precipitation, but it would seem that the overforecast surface Lows in both the PE and HFM over south Texas would have been more likely to be interpreted as precipitation producers than the other models.

At 300 mb (figs. 15A and 15B) the HFM was clearly the best forecast both as to the isotach maximum and the general pattern as well as the location and depth of the Canadian Low center near James Bay.

Summary

The concensus of the 5-man jury of forecasters was that the hemispheric fine-mesh forecast was clearly superior to the other contending models. The nested grid model was a close second, the operational coarse mesh P.E. was third, and the 9-Layer was lost. This ranking was also true for all the other test forecasts which were evaluated. This result was affirmed also by the independent statistical verification results, which are not included in this report.

Despite improvements in the circulation forecasts over the coarse mesh model, there was not a corresponding clear improvement in precipitation forecasts, although the HFM still appeared to have an edge. However, forecaster interpretation of the improved fine-mesh would have been better.

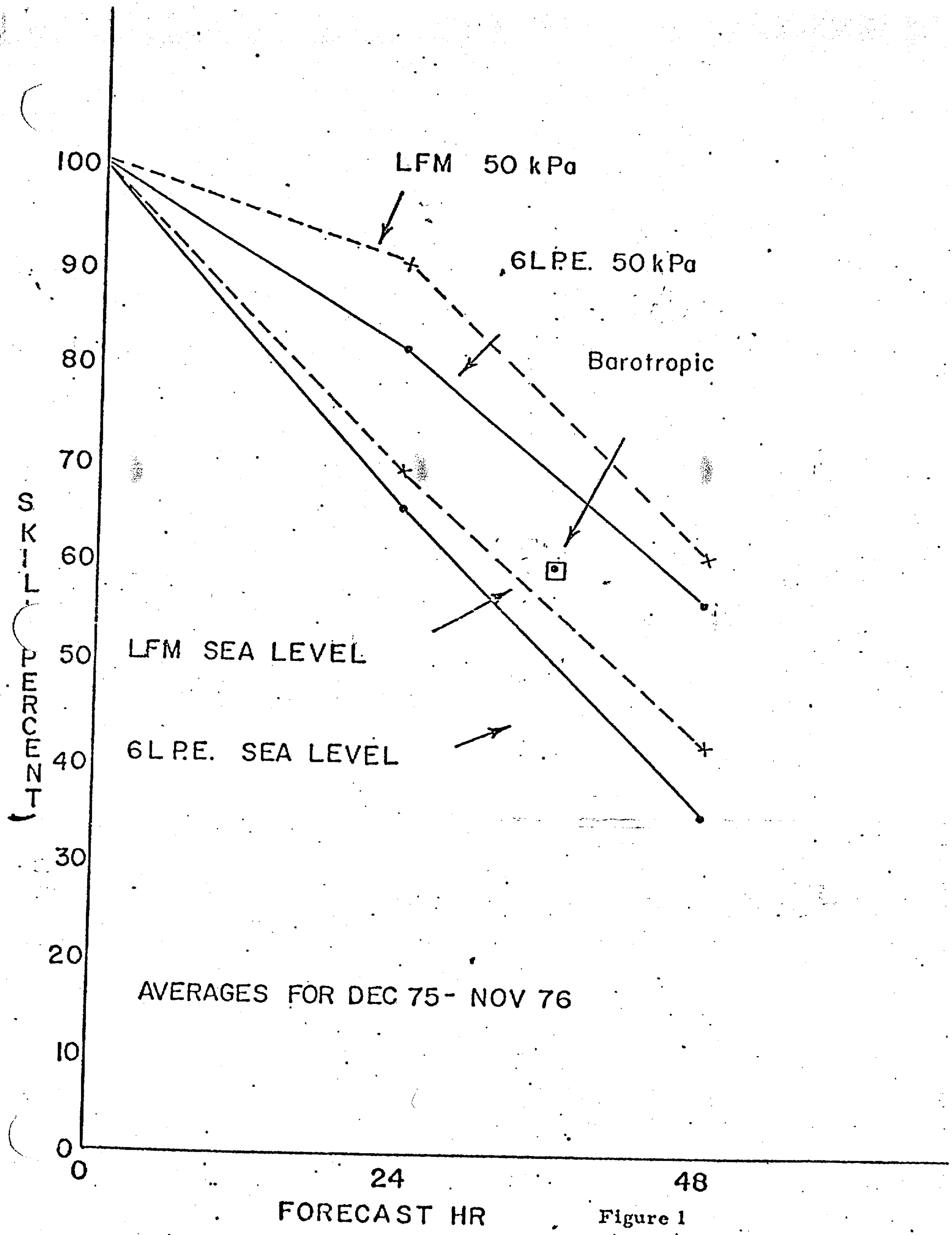
Final Section

NMC also plans to replace the current LFM model in August 1977, with a finer mesh version (LFM II) using pressure gradient averaging but it will require additional running time which will be limited to 30 minutes. This will allow for a mesh length about 2/3 of the present LFM, or about 127 km. Furthermore, later in the year it will be using boundary values from a more accurate finer-mesh hemispheric model, which could result in accuracy approaching the current MFM precipitation forecast model with a mesh length of 100 km. Therefore, this precipitation version of the MFM may not be needed any longer. The MFM would,of course, still be used as a hurricane forecast model. The longer running times of the LFM II and the finer-mesh hemispheric models would not leave enough time in the 12-hour forecast cycle with present computer usage to run the MFM hurricane model. It is therefore envisaged that on days when the MFM forecast is needed, the finer-mesh regional and hemispheric models will not be run and the coarse mesh versions will have to be run instead.

This would obviously affect the continuity of forecasts. The only long term solution would be a new plan of computer usage, such as running the MFM on a separate computer as a checkout job.

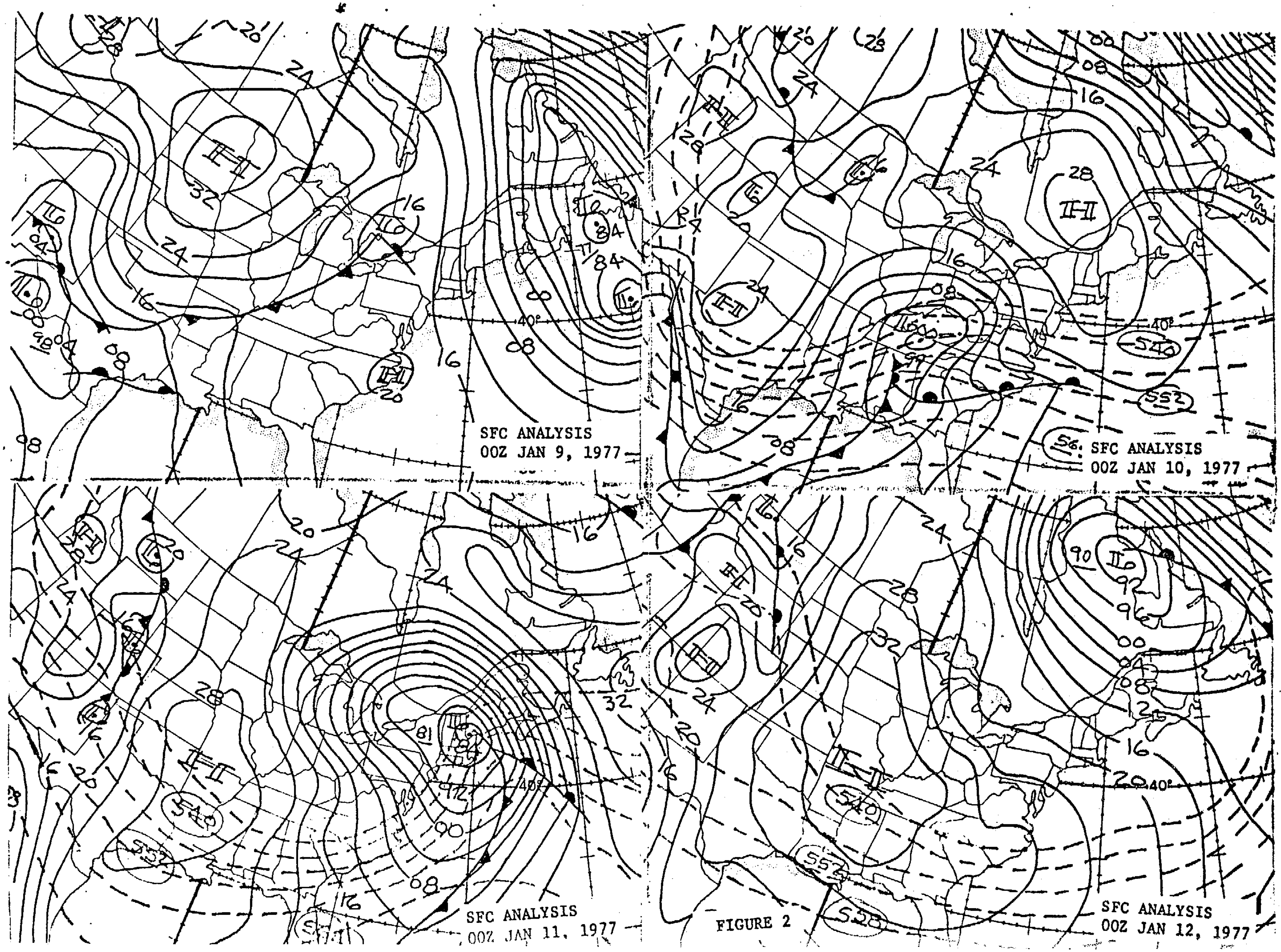
References

(1) Shuman, F. G., "Plans of the NMC for Numerical Weather Prediction, NMC Office Note 144, April 1977.



LFM 50 kPa
6L P.E. 50 kPa
Barotropic
LFM SEA LEVEL
6L P.E. SEA LEVEL
AVERAGES FOR DEC 75 - NOV 76
SKILL PERCENT
100
90
80
70
60
50
40
30
20
10
0
0
24
48
FORECAST HR

Figure 1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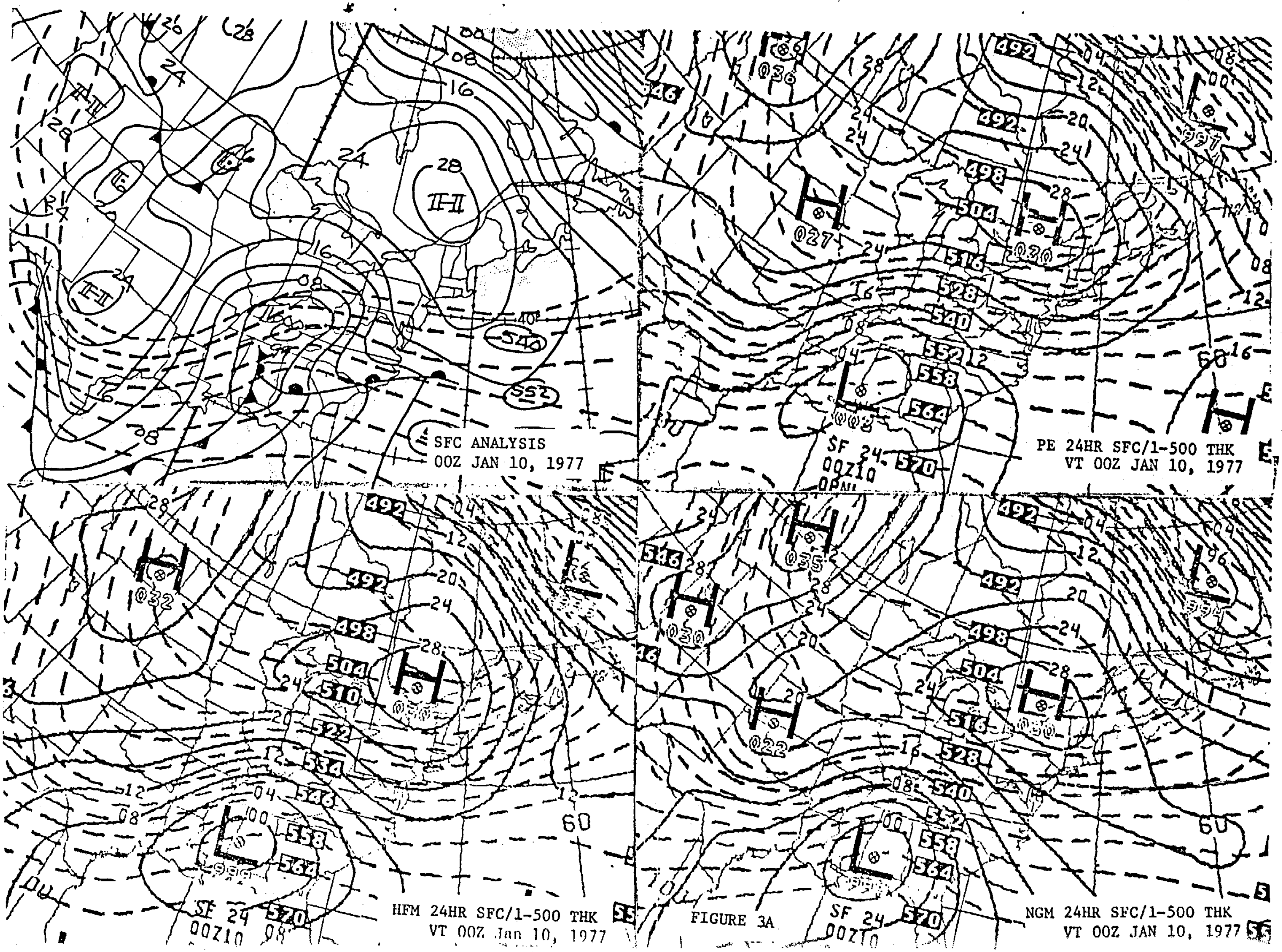
00Z JAN 9, 1977
SFC ANALYSIS
00Z JAN 10, 1977
SFC ANALYSIS
00Z JAN 11, 1977
SFC ANALYSIS
00Z JAN 12, 1977

FIGURE 2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PE 24HR SFC/1-500 THK
VT 00Z JAN 10, 1977
HFM 24HR SFC/1-500 THK
VT 00Z Jan 10, 1977
NGM 24HR SFC/1-500 THK
VT 00Z JAN 10, 1977

FIGURE 3A

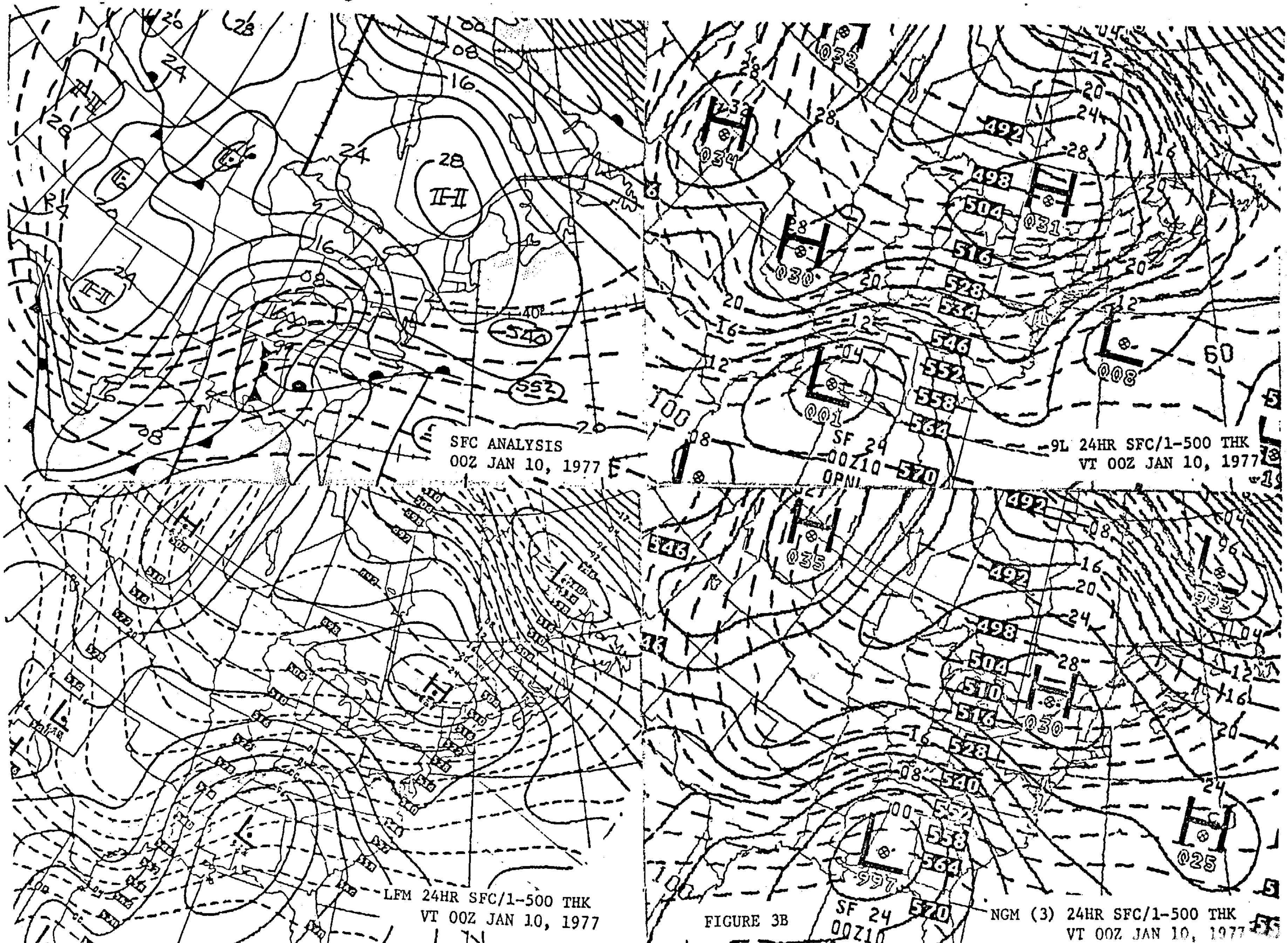

SFC ANALYSIS
00Z JAN 10, 1977
9L 24HR SFC/1-500 THK
VT 00Z JAN 10, 1977
SF 24
00Z10
LFM 24HR SFC/1-500 THK
VT 00Z JAN 10, 1977
NGM (3) 24HR SFC/1-500 THK
VT 00Z JAN 10, 1977

FIGURE 3B

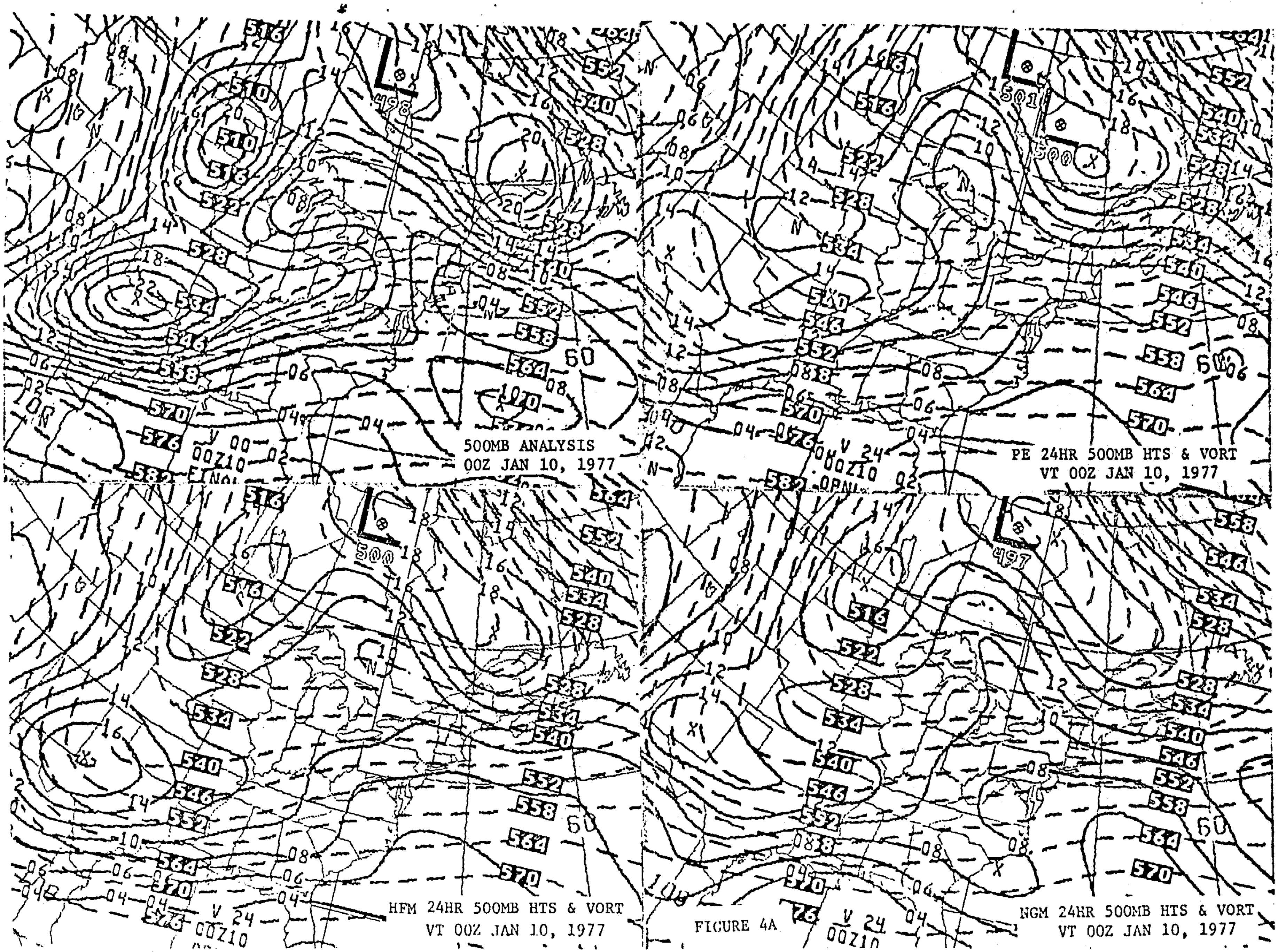
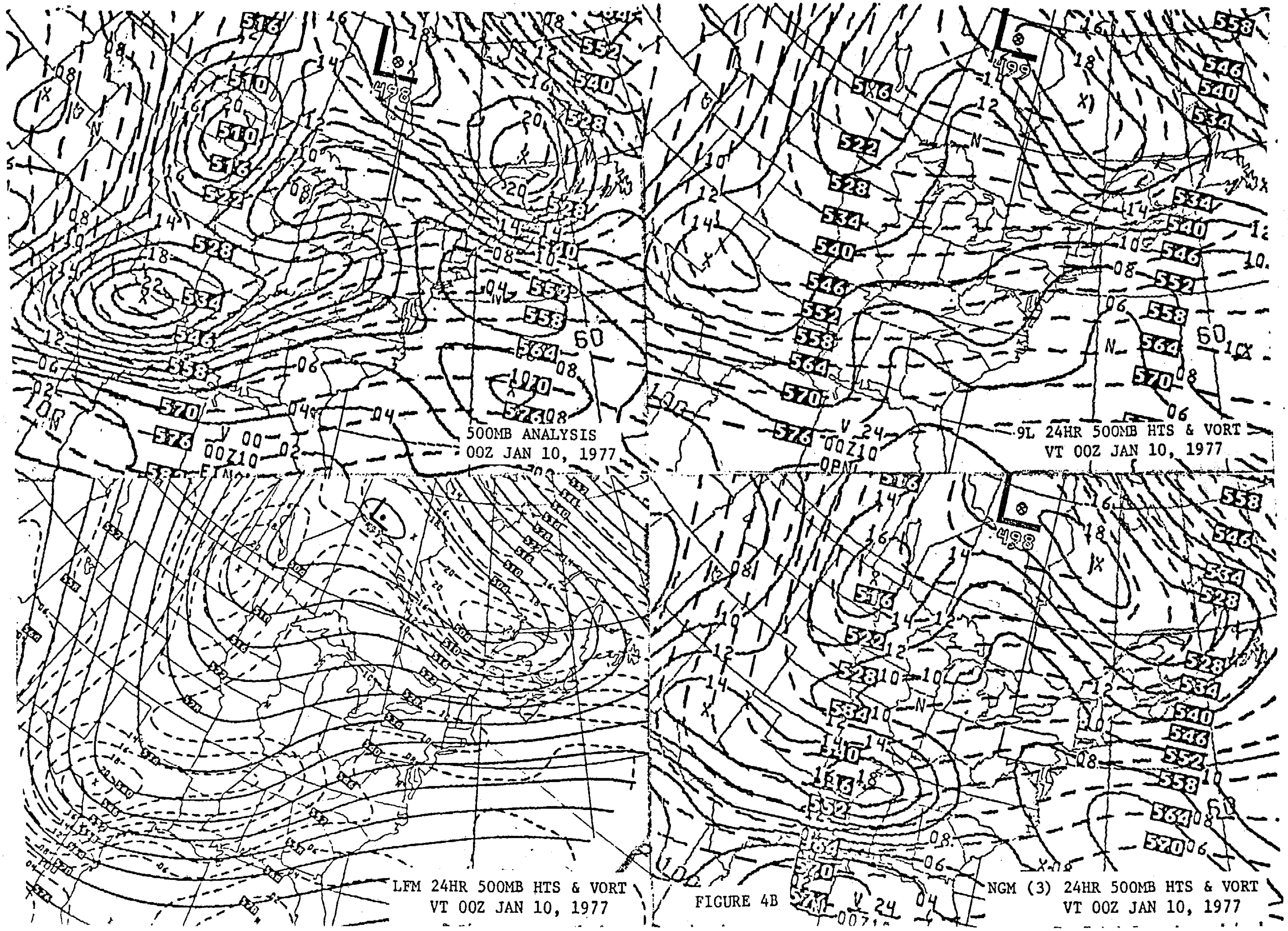

500MB ANALYSIS
00Z JAN 10, 1977
PE 24HR 500MB HTS & VORT
VT 00Z JAN 10, 1977
HFM 24HR 500MB HTS & VORT
VT 00Z JAN 10, 1977
NGM 24HR 500MB HTS & VORT
VT 00Z JAN 10, 1977

FIGURE 4A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VT 00Z JAN 10, 1977
LFM 24HR 500MB HTS & VORT
VT 00Z JAN 10, 1977
NGM (3) 24HR 500MB HTS & VORT
VT 00Z JAN 10, 1977

FIGURE 4B

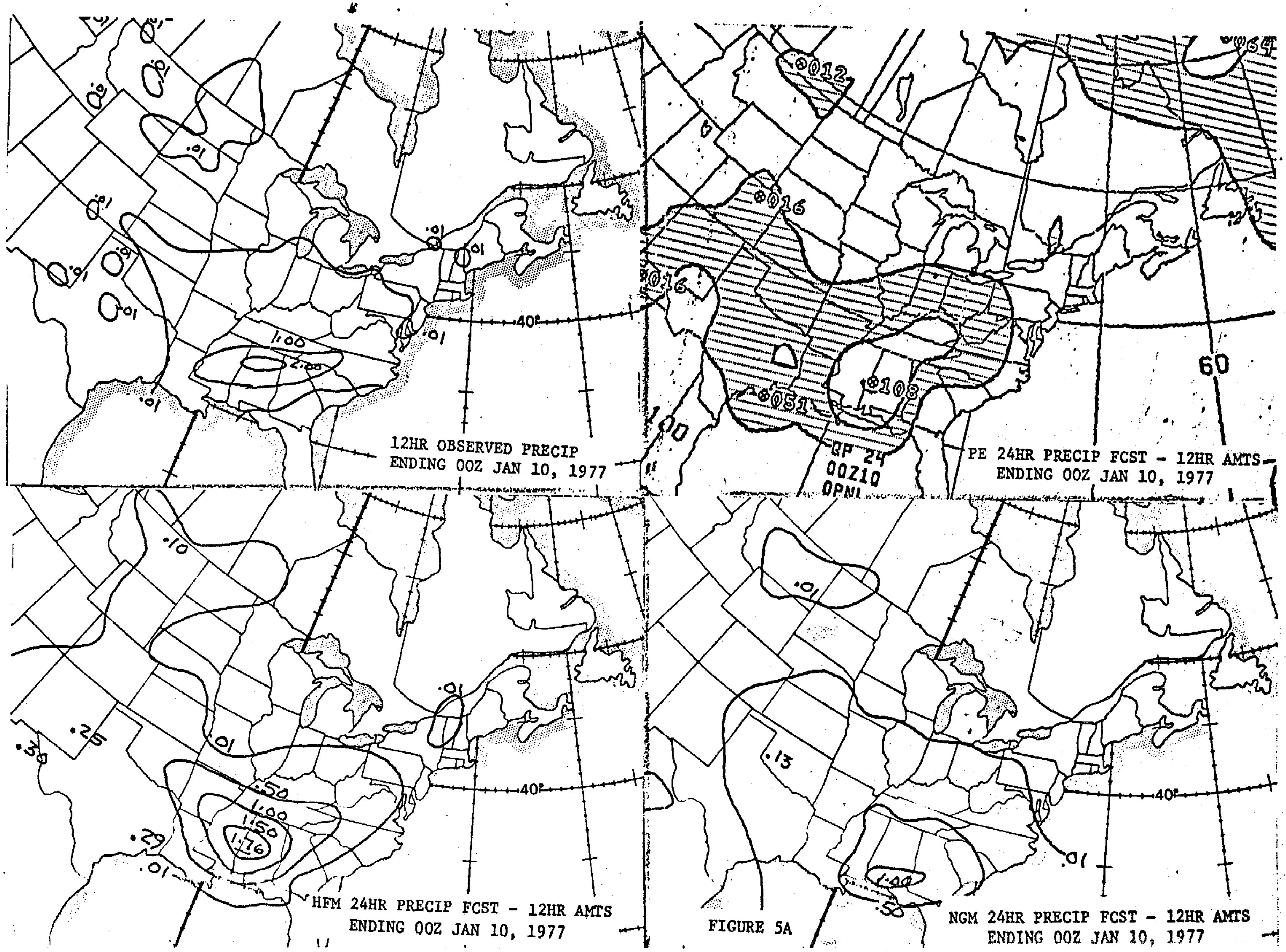
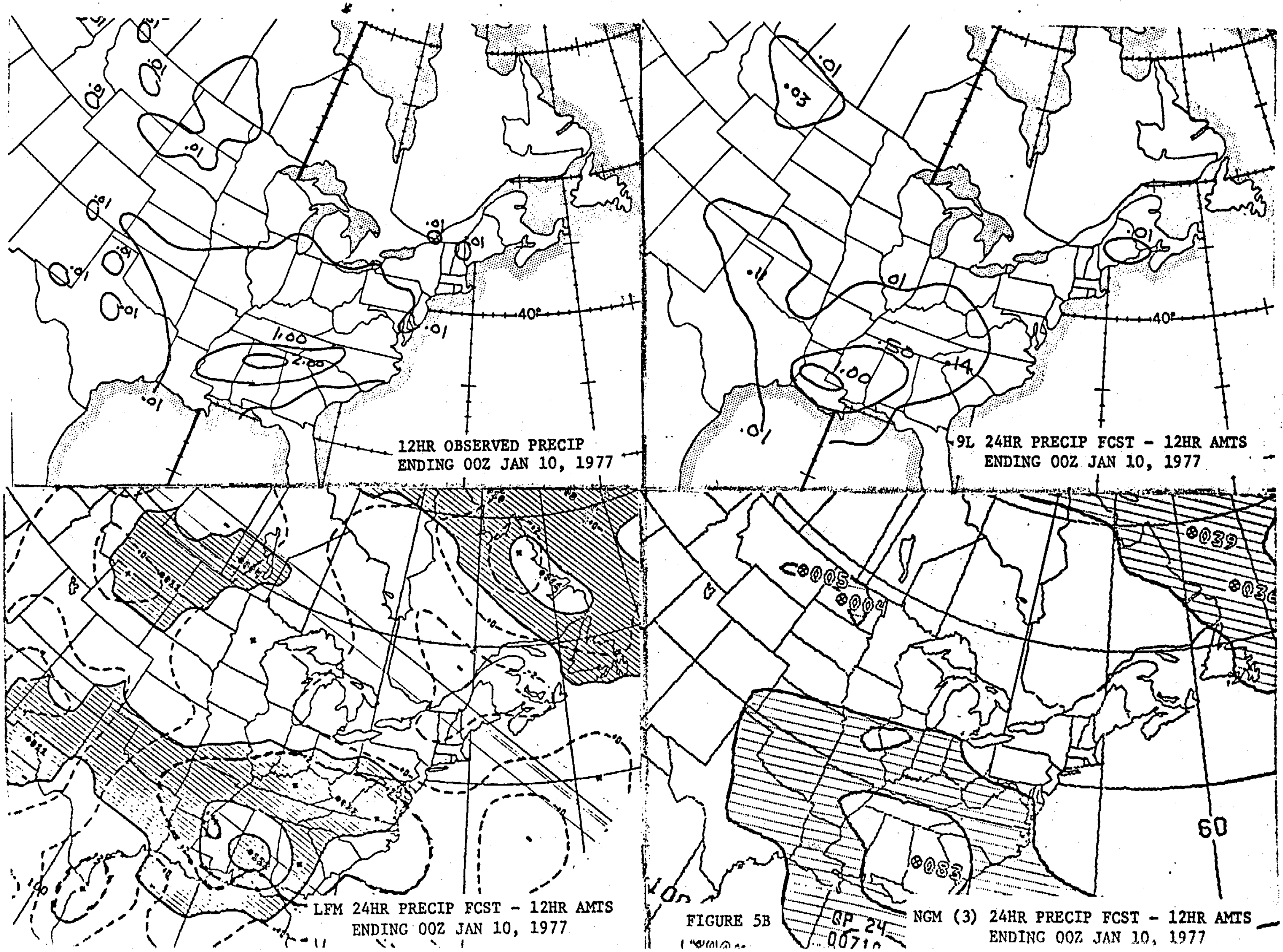

12HR OBSERVED PRECIP
ENDING 00Z JAN 10, 1977
PE 24HR PRECIP FCST - 12HR AMTS
ENDING 00Z JAN 10, 1977
HFM 24HR PRECIP FCST - 12HR AMTS
ENDING 00Z JAN 10, 1977
NGM 24HR PRECIP FCST - 12HR AMTS
ENDING 00Z JAN 10, 1977
QP 24
00Z10
OPNL
40°
60
.01
1.00
2.00
.10
.25
.30
.29
.50
1.50
1.76
.13
012
016
051
108

FIGURE 5A



12HR OBSERVED PRECIP
ENDING 00Z JAN 10, 1977

9L 24HR PRECIP FCST - 12HR AMTS
ENDING 00Z JAN 10, 1977

LFM 24HR PRECIP FCST - 12HR AMTS
ENDING 00Z JAN 10, 1977

FIGURE 5B

NGM (3) 24HR PRECIP FCST - 12HR AMTS
ENDING 00Z JAN 10, 1977

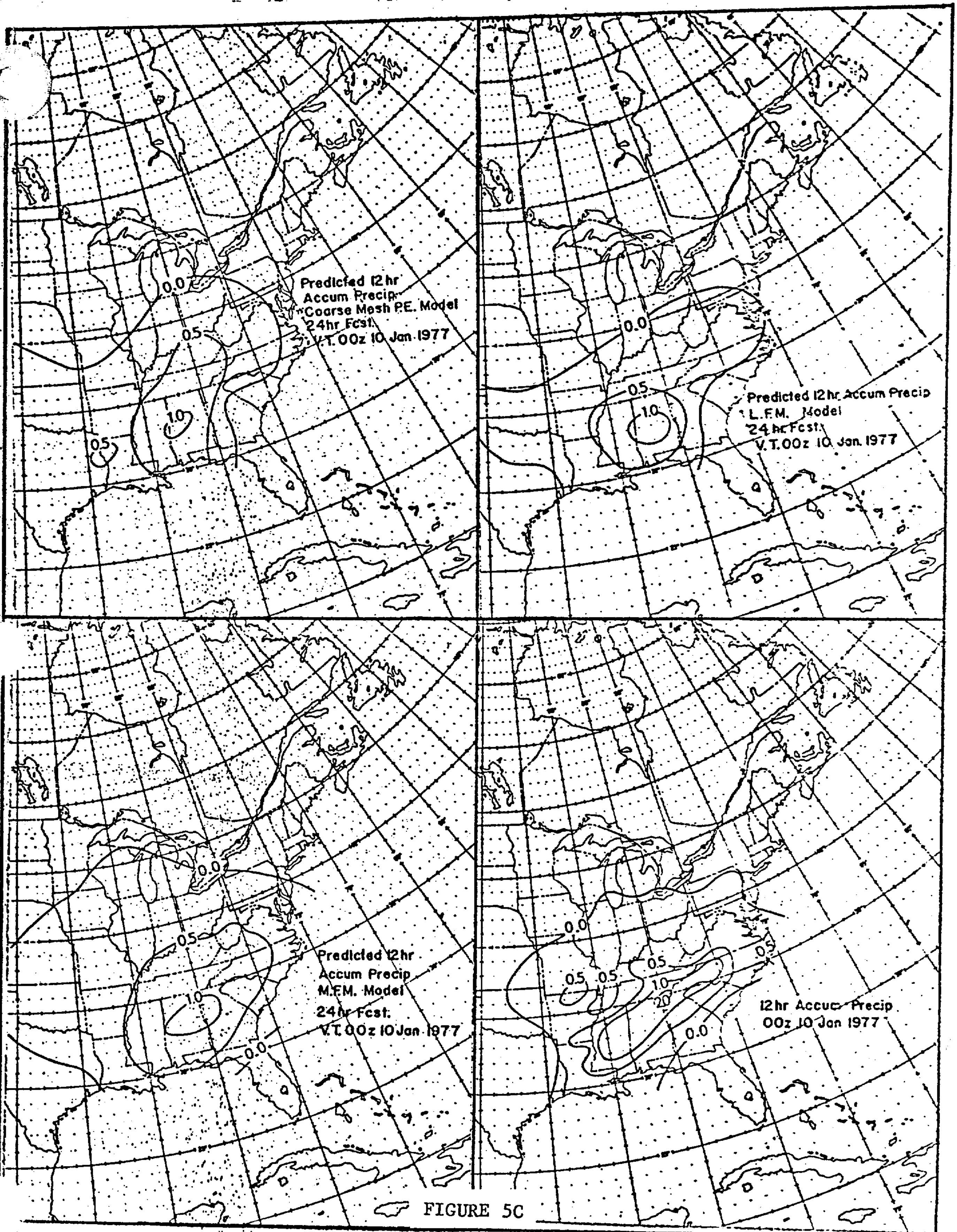

Predicted 12 hr
Accum Precip
Coarse Mesh P.E. Model
24 hr Fcst.
V.T. 00z 10 Jan 1977
0.0
0.5
1.0
0.5
Predicted 12 hr Accum Precip
L.F.M. Model
24 hr Fcst.
V.T. 00z 10 Jan 1977
0.0
0.5
1.0
Predicted 12 hr
Accum Precip
M.F.M. Model
24 hr Fcst.
V.T. 00z 10 Jan 1977
0.0
0.5
1.0
0.0
12 hr Accum Precip
00z 10 Jan 1977
0.0
0.5
0.5
0.5
1.0
2.0
0.0
0.5

FIGURE 5C

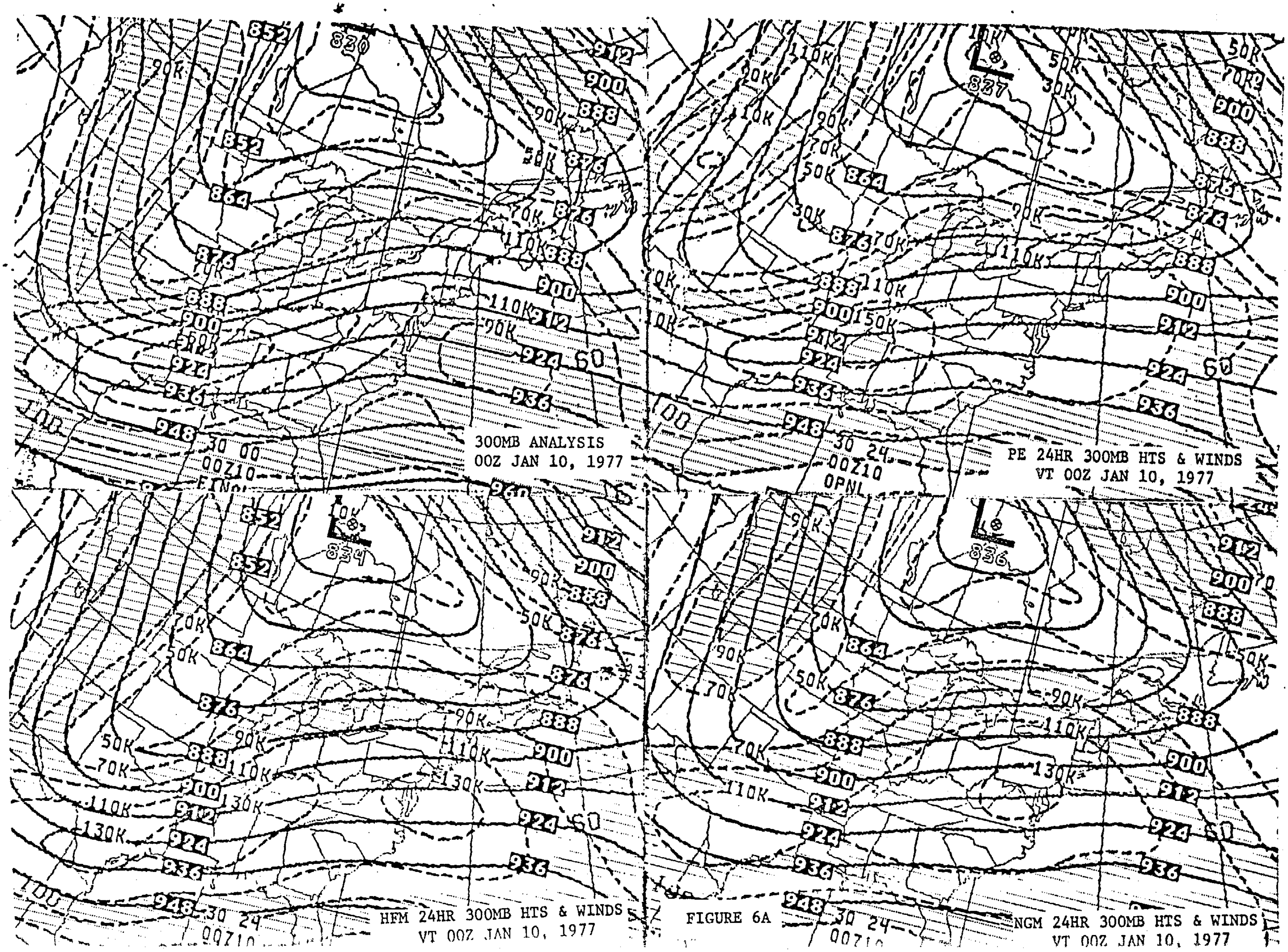
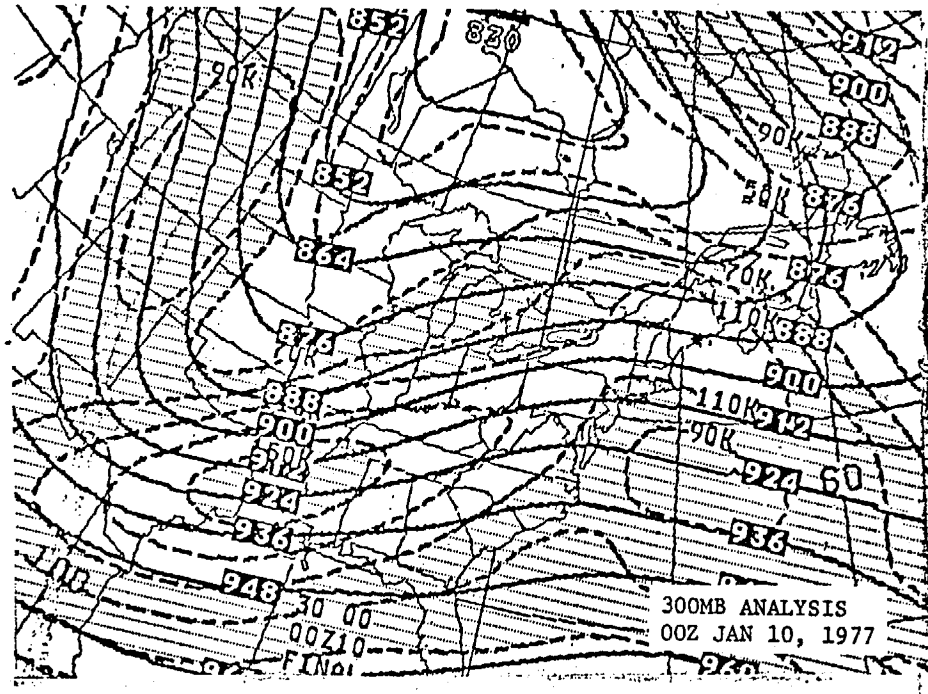
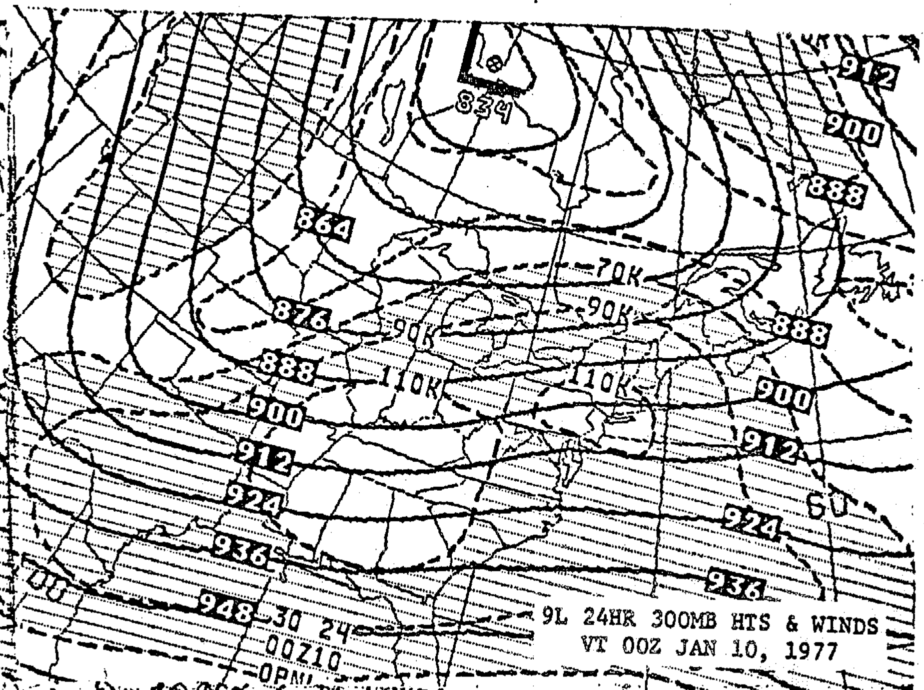

300MB ANALYSIS
00Z JAN 10, 1977
PE 24HR 300MB HTS & WINDS
VT 00Z JAN 10, 1977
HFM 24HR 300MB HTS & WINDS
VT 00Z JAN 10, 1977
NGM 24HR 300MB HTS & WINDS
VT 00Z JAN 10, 1977

FIGURE 6A



300MB ANALYSIS
00Z JAN 10, 1977



9L 24HR 300MB HTS & WINDS
VT 00Z JAN 10, 1977

NO 24HR 300MB LFM

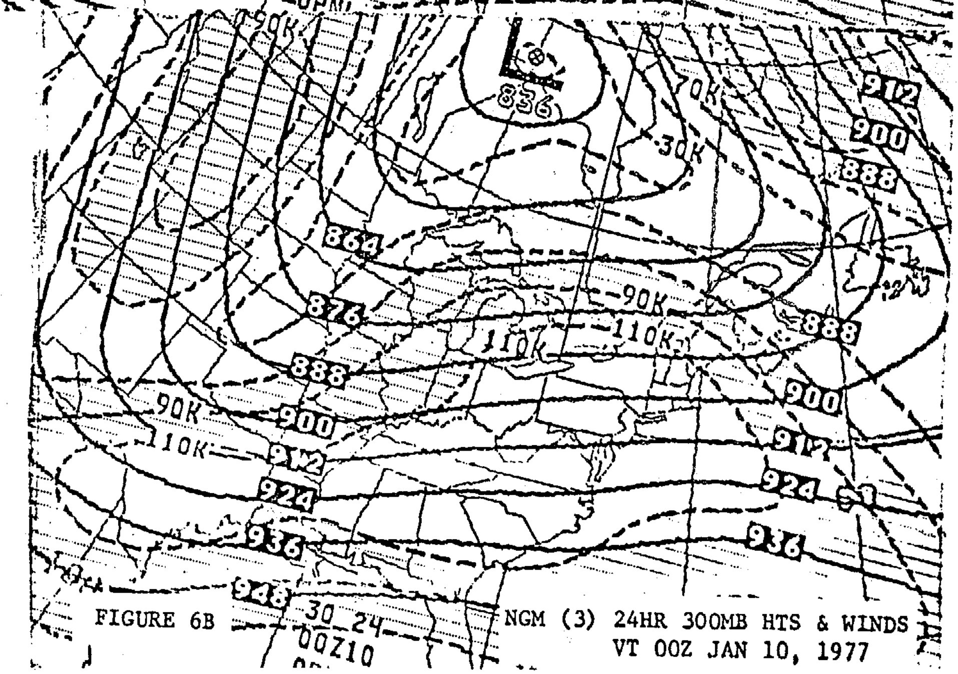


FIGURE 6B

NGM (3) 24HR 300MB HTS & WINDS
VT 00Z JAN 10, 1977

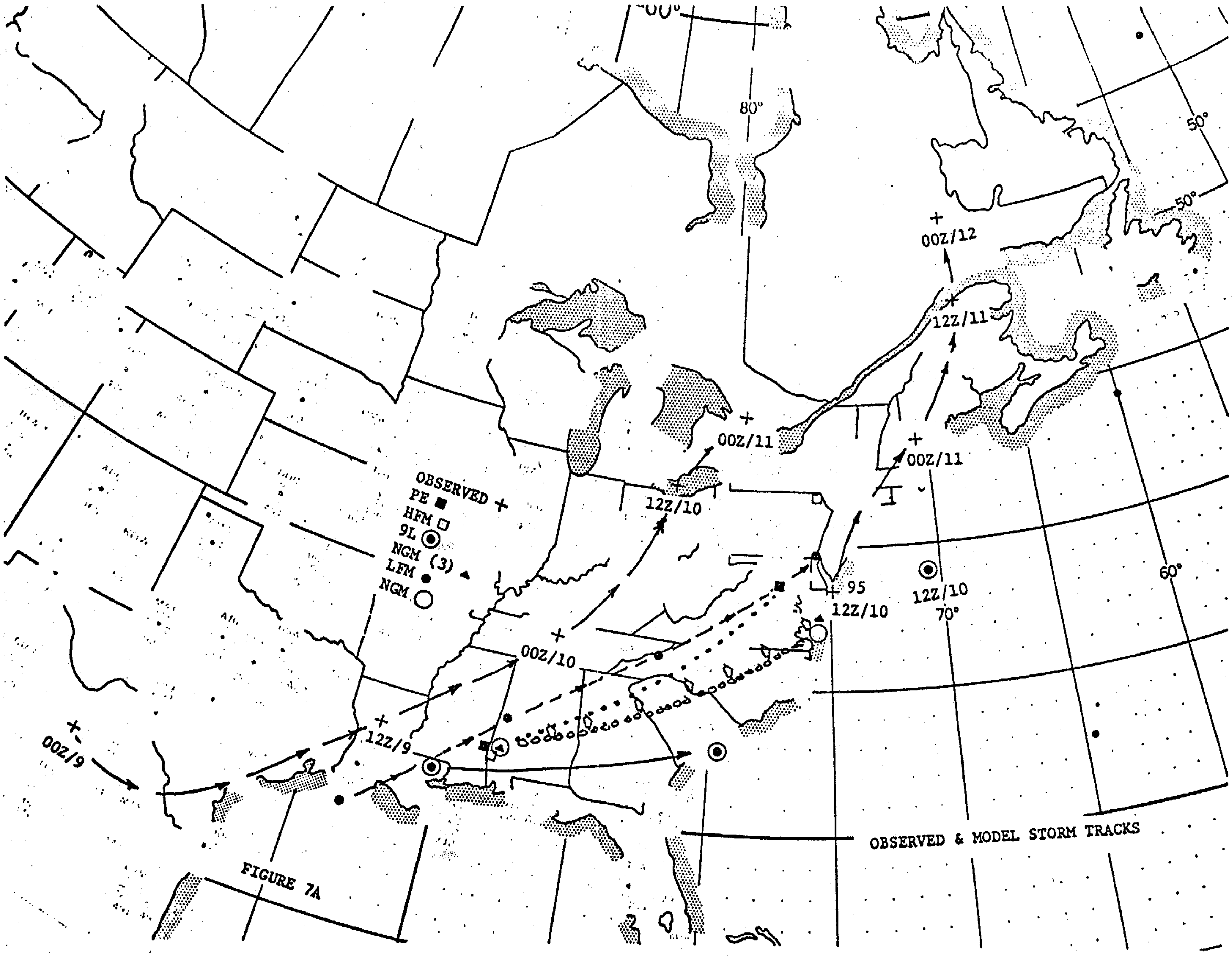
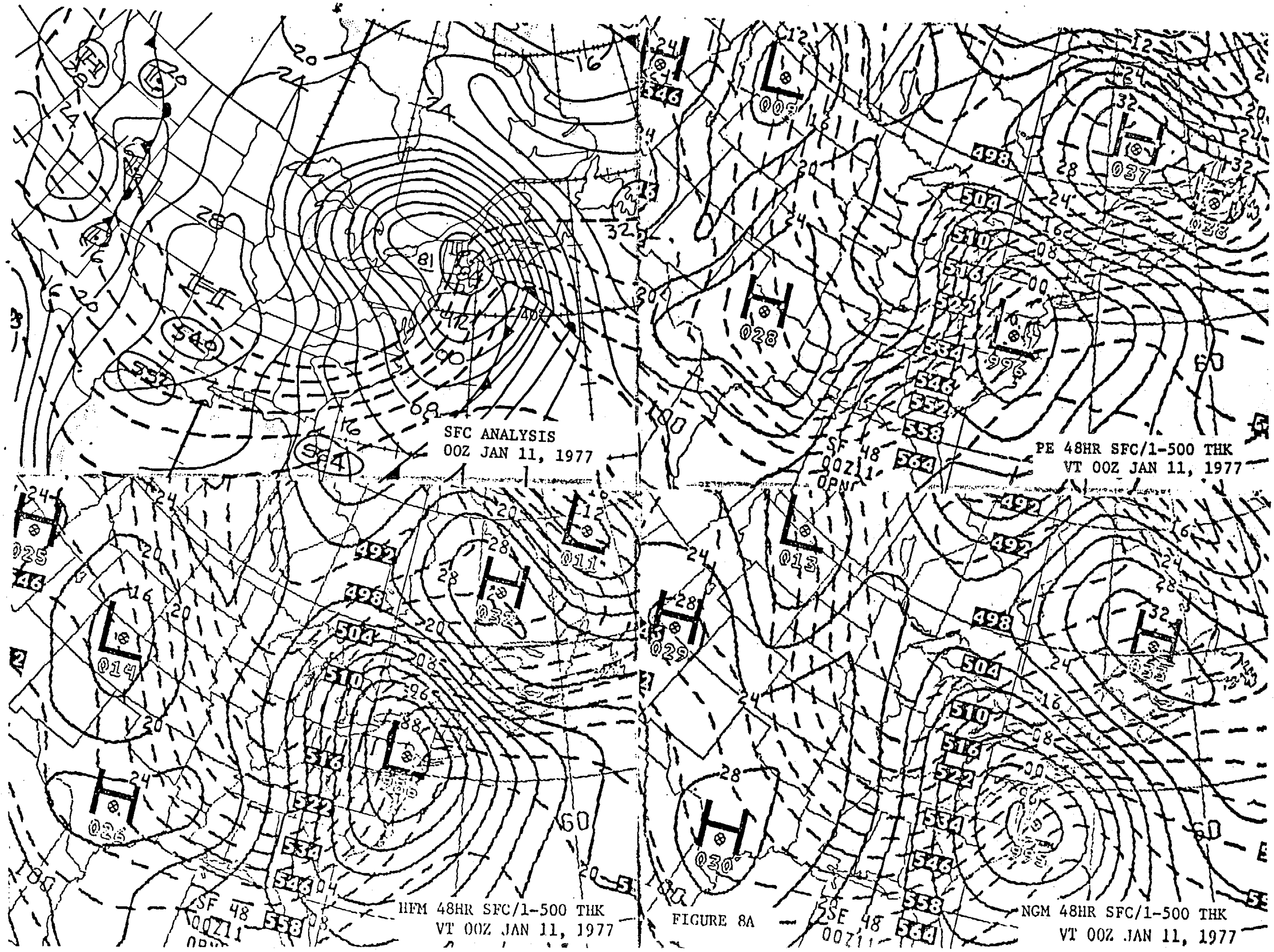
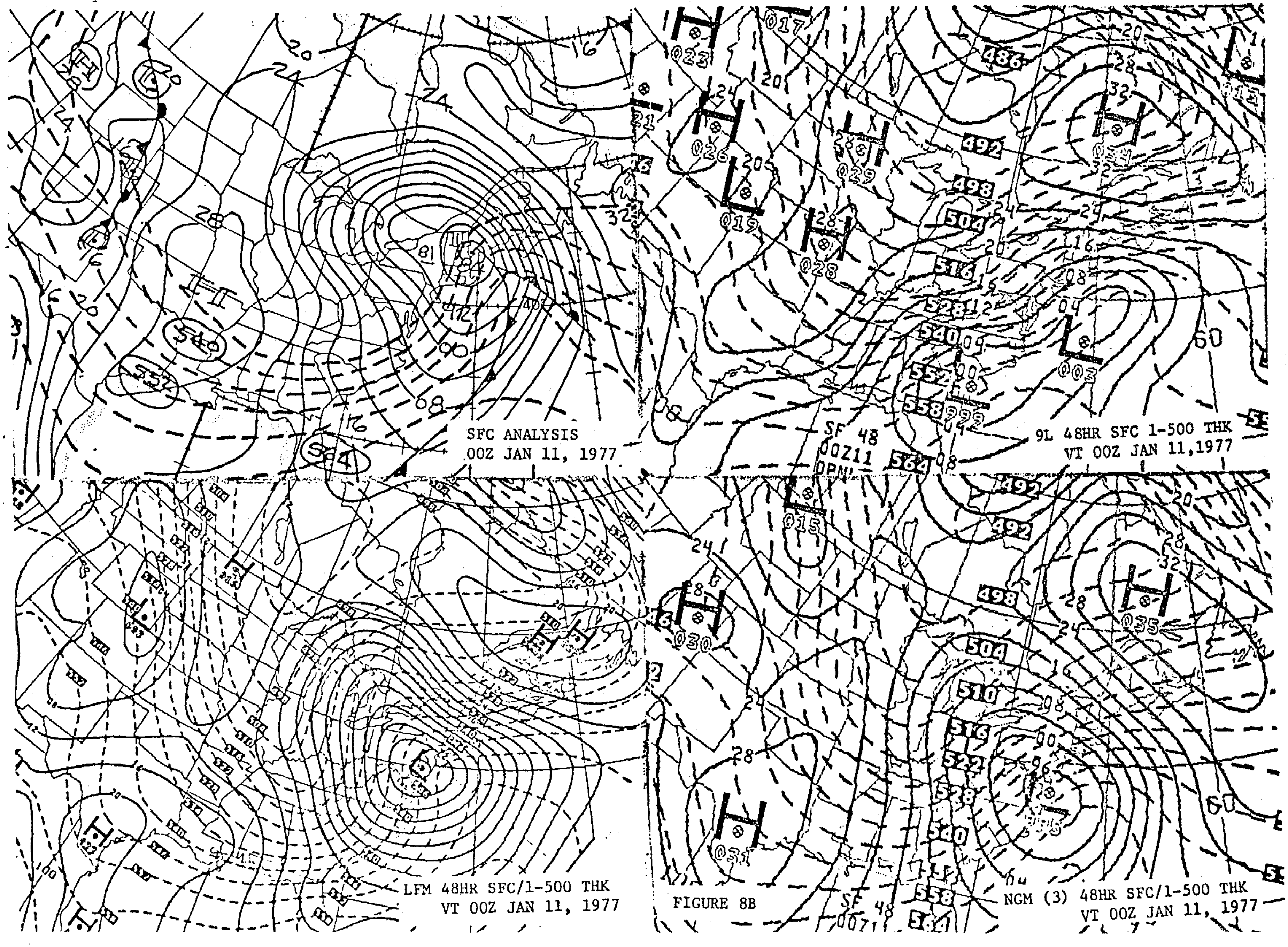

OBSERVED +
PE
HFM
9L
NGM (3)
LFM
NGM
00Z/9
12Z/9
00Z/10
12Z/10
00Z/11
12Z/11
00Z/12
95
70°
60°
80°
50°
OBSERVED & MODEL STORM TRACKS

FIGURE 7A



SFC ANALYSIS
00Z JAN 11, 1977
PE 48HR SFC/1-500 THK
VT 00Z JAN 11, 1977
HFM 48HR SFC/1-500 THK
VT 00Z JAN 11, 1977
NGM 48HR SFC/1-500 THK
VT 00Z JAN 11, 1977

FIGURE 8A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00Z JAN 11, 1977
9L 48HR SFC 1-500 THK
VT 00Z JAN 11,1977
SF 48
00Z11
OPNL
LFM 48HR SFC/1-500 THK
VT 00Z JAN 11, 1977
NGM (3) 48HR SFC/1-500 THK
VT 00Z JAN 11, 1977

FIGURE 8B

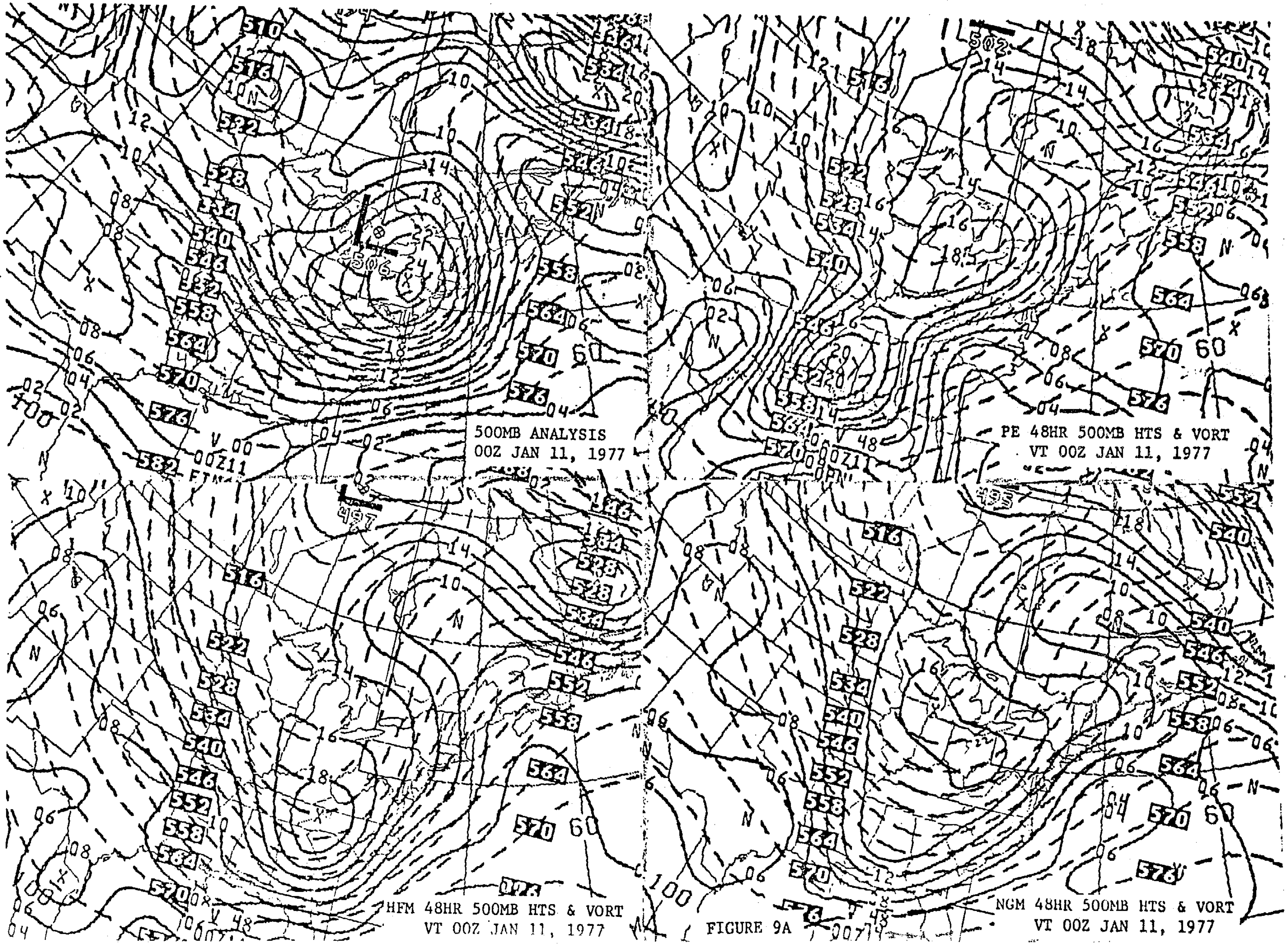

500MB ANALYSIS
00Z JAN 11, 1977
PE 48HR 500MB HTS & VORT
VT 00Z JAN 11, 1977
HFM 48HR 500MB HTS & VORT
VT 00Z JAN 11, 1977
NGM 48HR 500MB HTS & VORT
VT 00Z JAN 11, 1977

FIGURE 9A

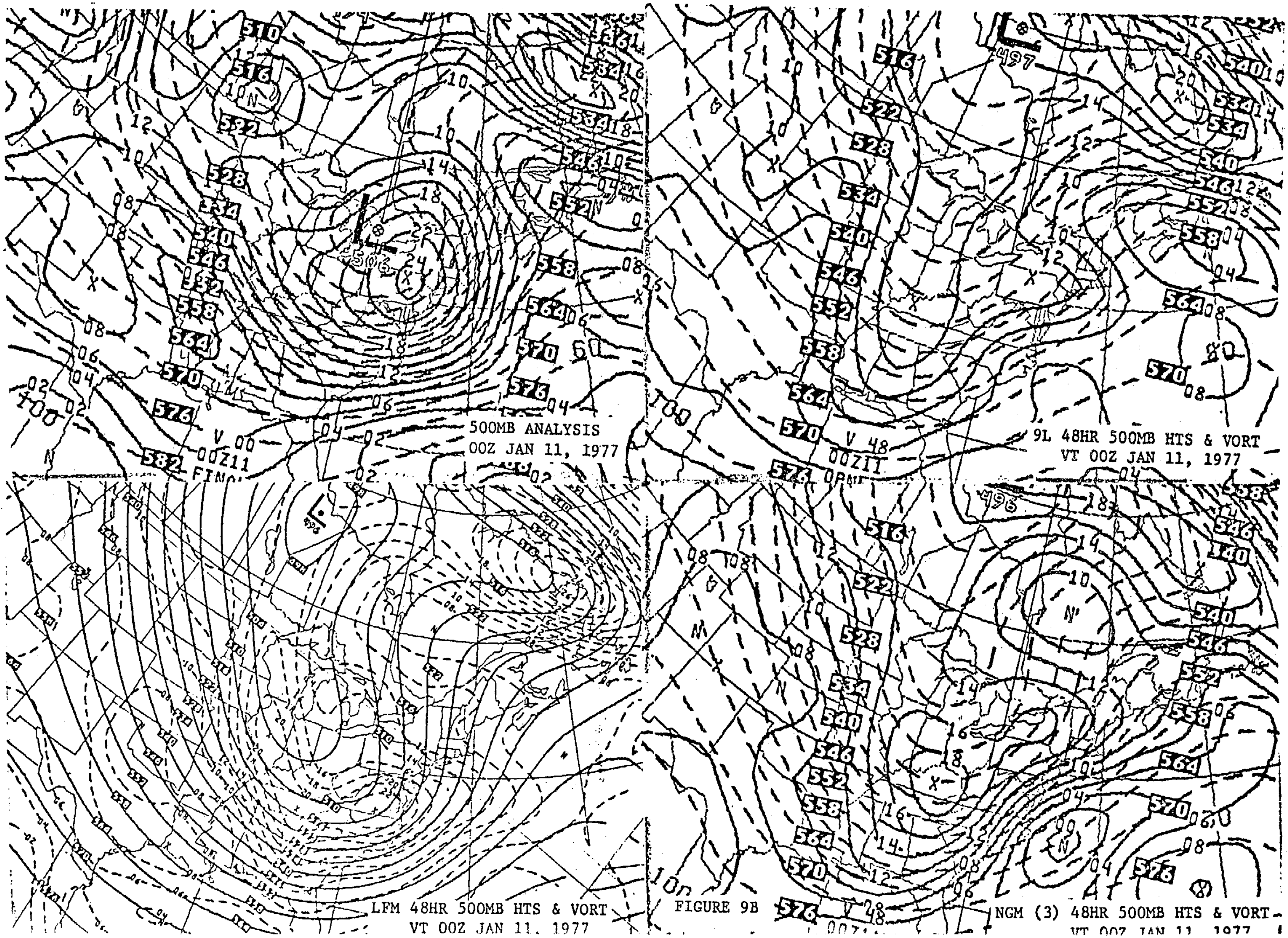

500MB ANALYSIS
00Z JAN 11, 1977
9L 48HR 500MB HTS & VORT
VT 00Z JAN 11, 1977
LFM 48HR 500MB HTS & VORT
VT 00Z JAN 11, 1977
NGM (3) 48HR 500MB HTS & VORT
VT 00Z JAN 11, 1977

FIGURE 9B

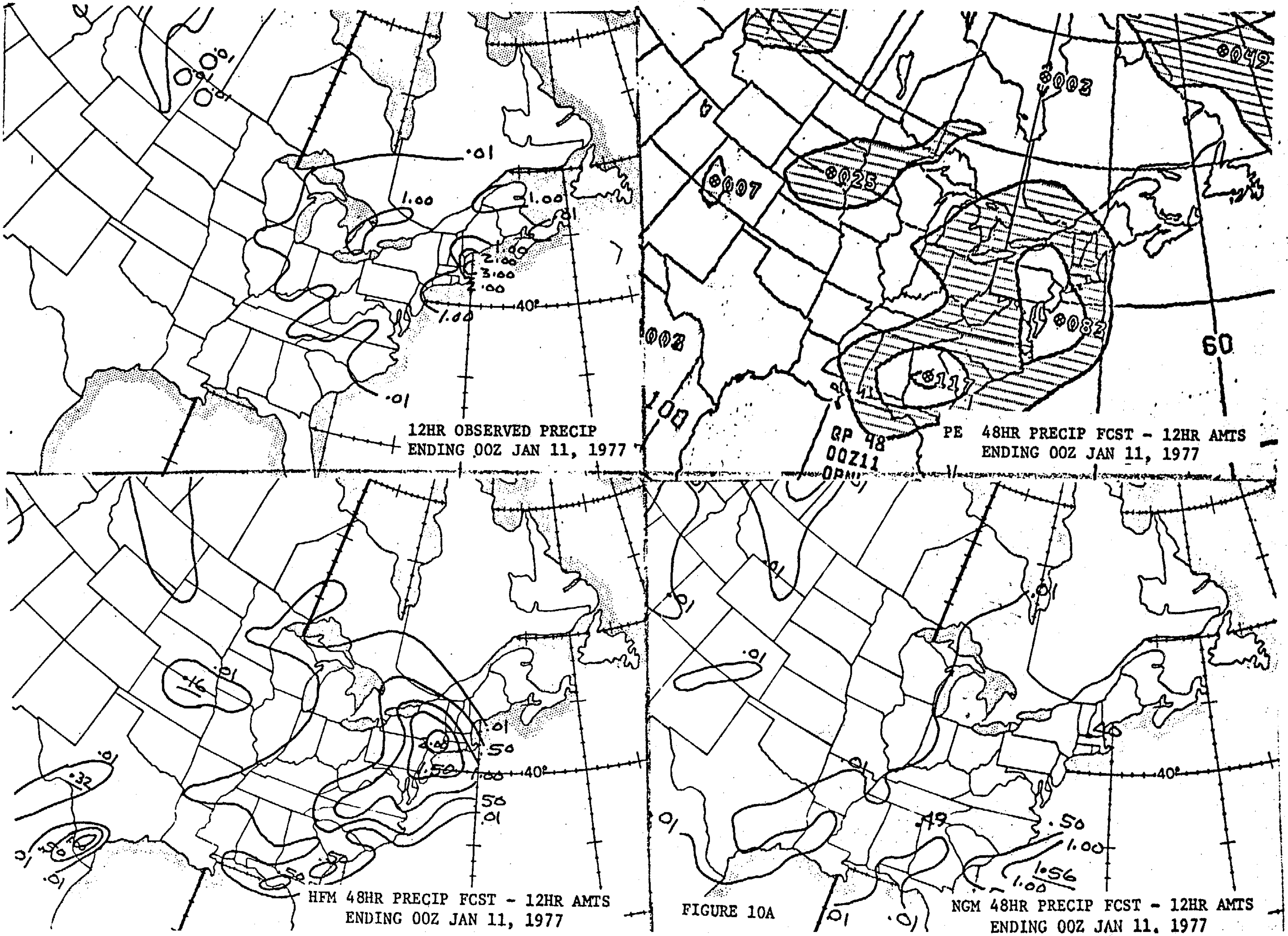

12HR OBSERVED PRECIP
ENDING 00Z JAN 11, 1977
PE 48HR PRECIP FCST - 12HR AMTS
ENDING 00Z JAN 11, 1977
HFM 48HR PRECIP FCST - 12HR AMTS
ENDING 00Z JAN 11, 1977
NGM 48HR PRECIP FCST - 12HR AMTS
ENDING 00Z JAN 11, 1977

FIGURE 10A

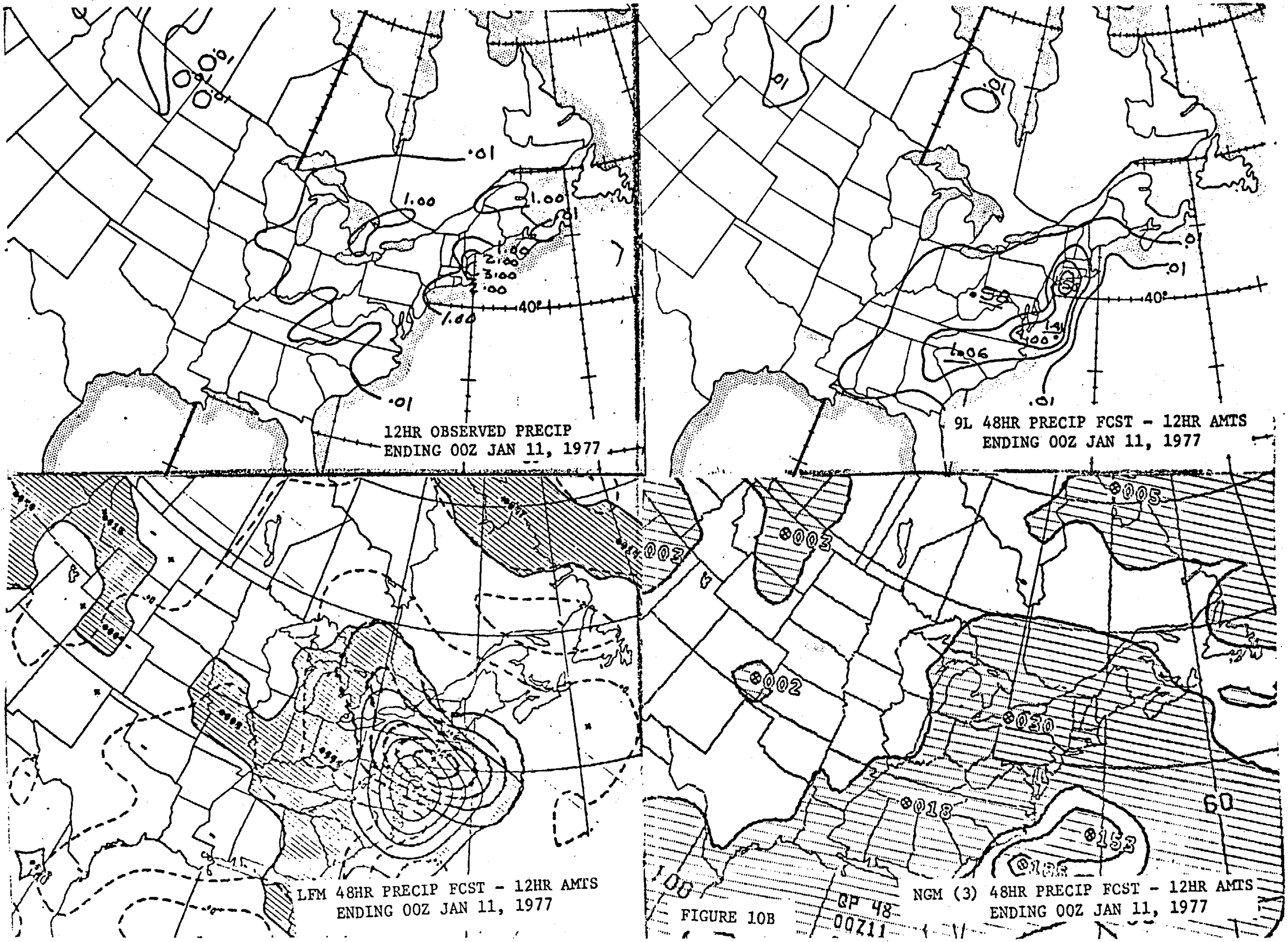

12HR OBSERVED PRECIP
ENDING 00Z JAN 11, 1977
.01
1.00
2.00
3.00
40°
9L 48HR PRECIP FCST - 12HR AMTS
ENDING 00Z JAN 11, 1977
.01
1.06
40°
LFM 48HR PRECIP FCST - 12HR AMTS
ENDING 00Z JAN 11, 1977
003
NGM (3) 48HR PRECIP FCST - 12HR AMTS
ENDING 00Z JAN 11, 1977
005
003
002
030
018
153
60
100
QP 48
00Z11

FIGURE 10B

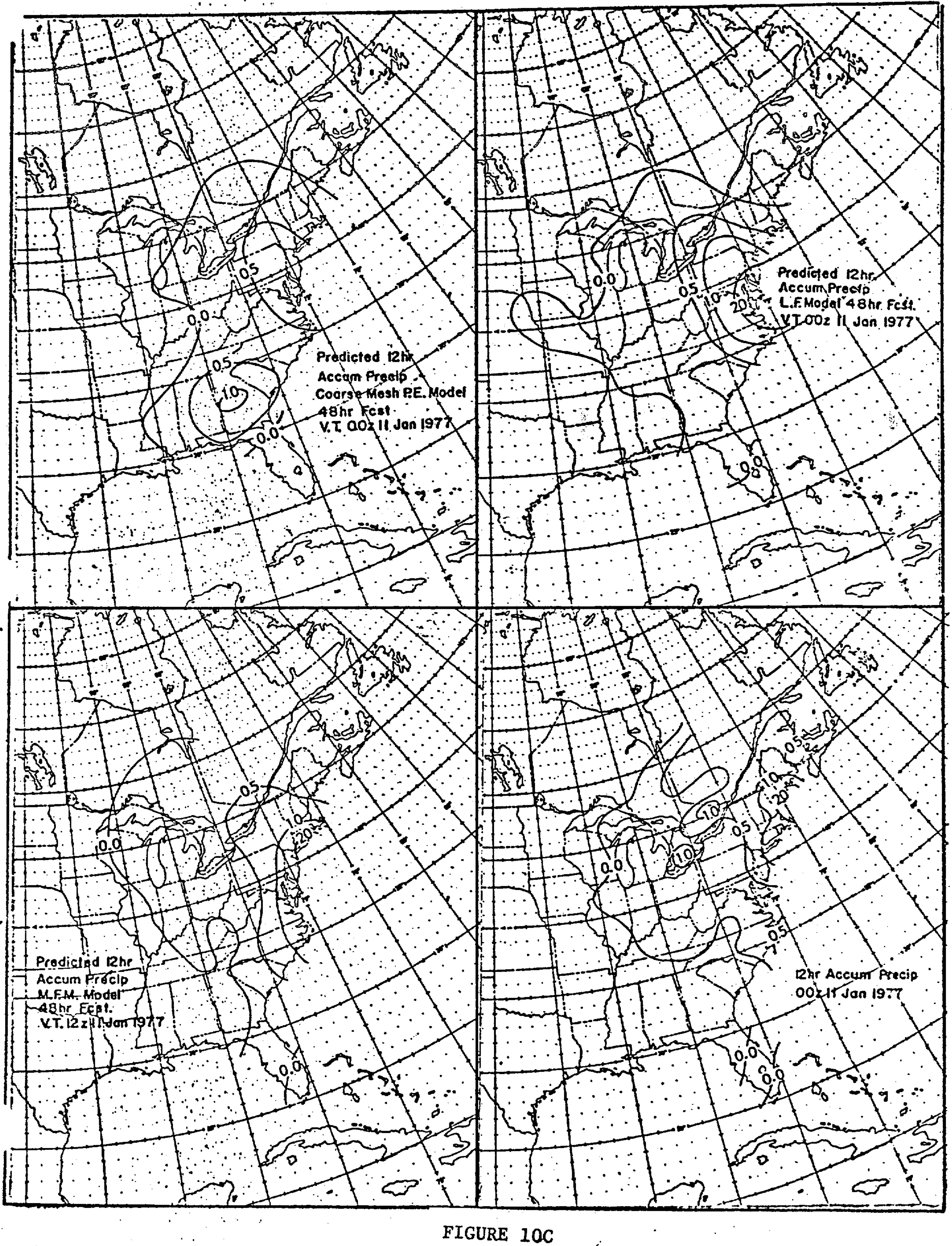

Predicted 12hr
Accum Precip
Coarse Mesh P.E. Model
48hr Fcst
V.T. 00z 11 Jan 1977
Predicted 12hr
Accum Precip
L.F. Model 48hr Fcst.
V.T. 00z 11 Jan 1977
Predicted 12hr
Accum Precip
M.F.M. Model
48hr Fcst.
V.T. 12z 11 Jan 1977
12hr Accum Precip
00z 11 Jan 1977

FIGURE 10C

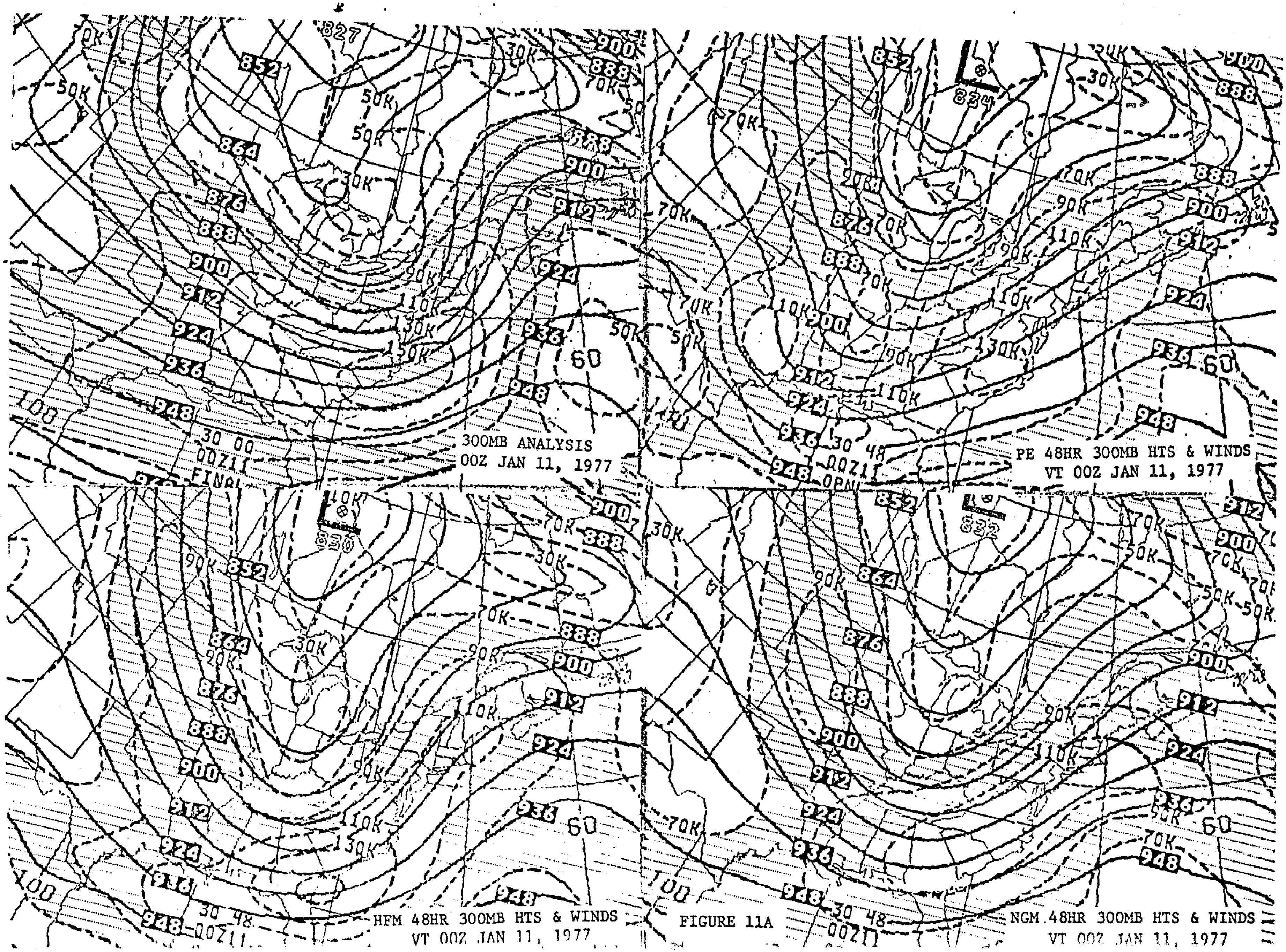
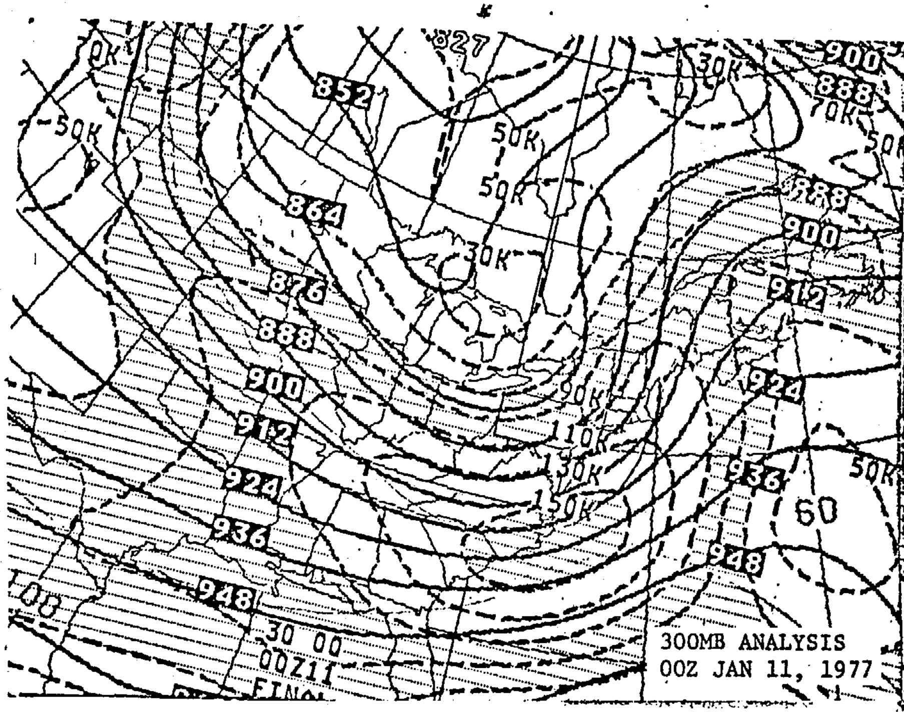
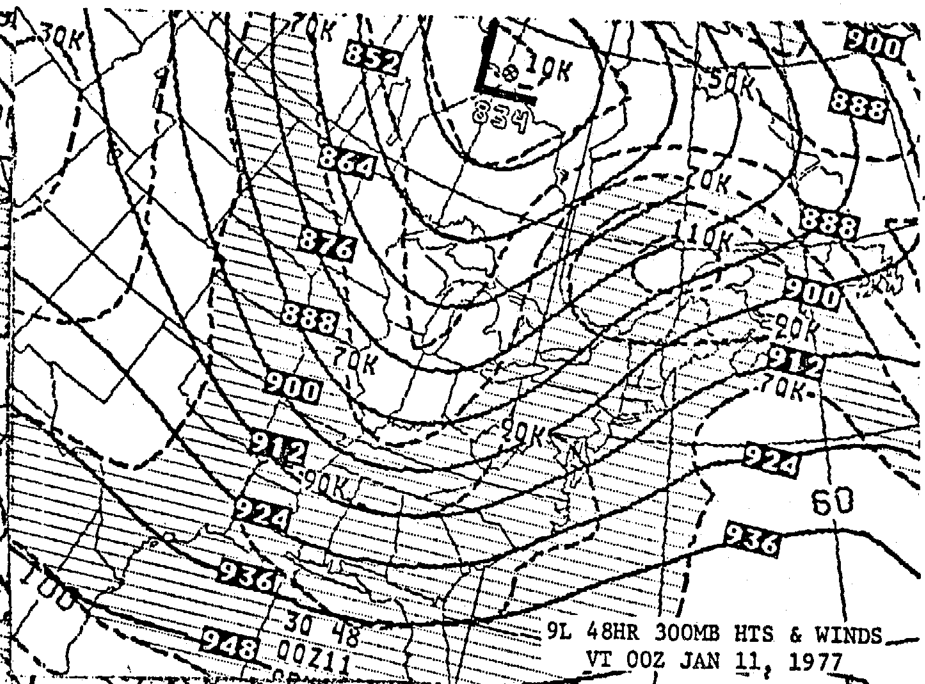

300MB ANALYSIS
00Z JAN 11, 1977
PE 48HR 300MB HTS & WINDS
VT 00Z JAN 11, 1977
HFM 48HR 300MB HTS & WINDS
VT 00Z JAN 11, 1977
NGM 48HR 300MB HTS & WINDS
VT 00Z JAN 11, 1977

FIGURE 11A



300MB ANALYSIS
00Z JAN 11, 1977



9L 48HR 300MB HTS & WINDS
VT 00Z JAN 11, 1977

NO 48HR 300MB LFM

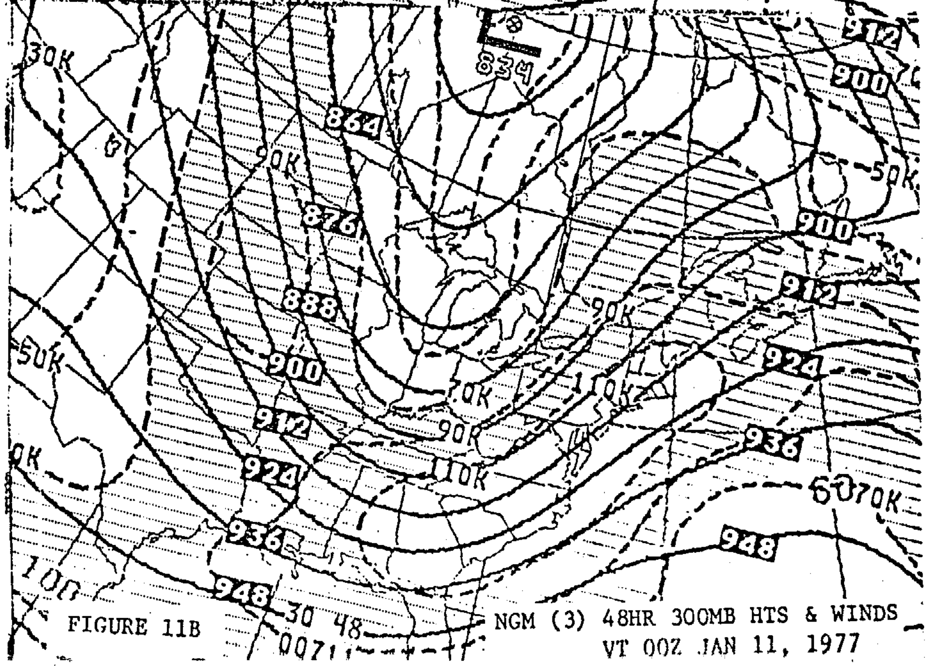


FIGURE 11B

NGM (3) 48HR 300MB HTS & WINDS
VT 00Z JAN 11, 1977

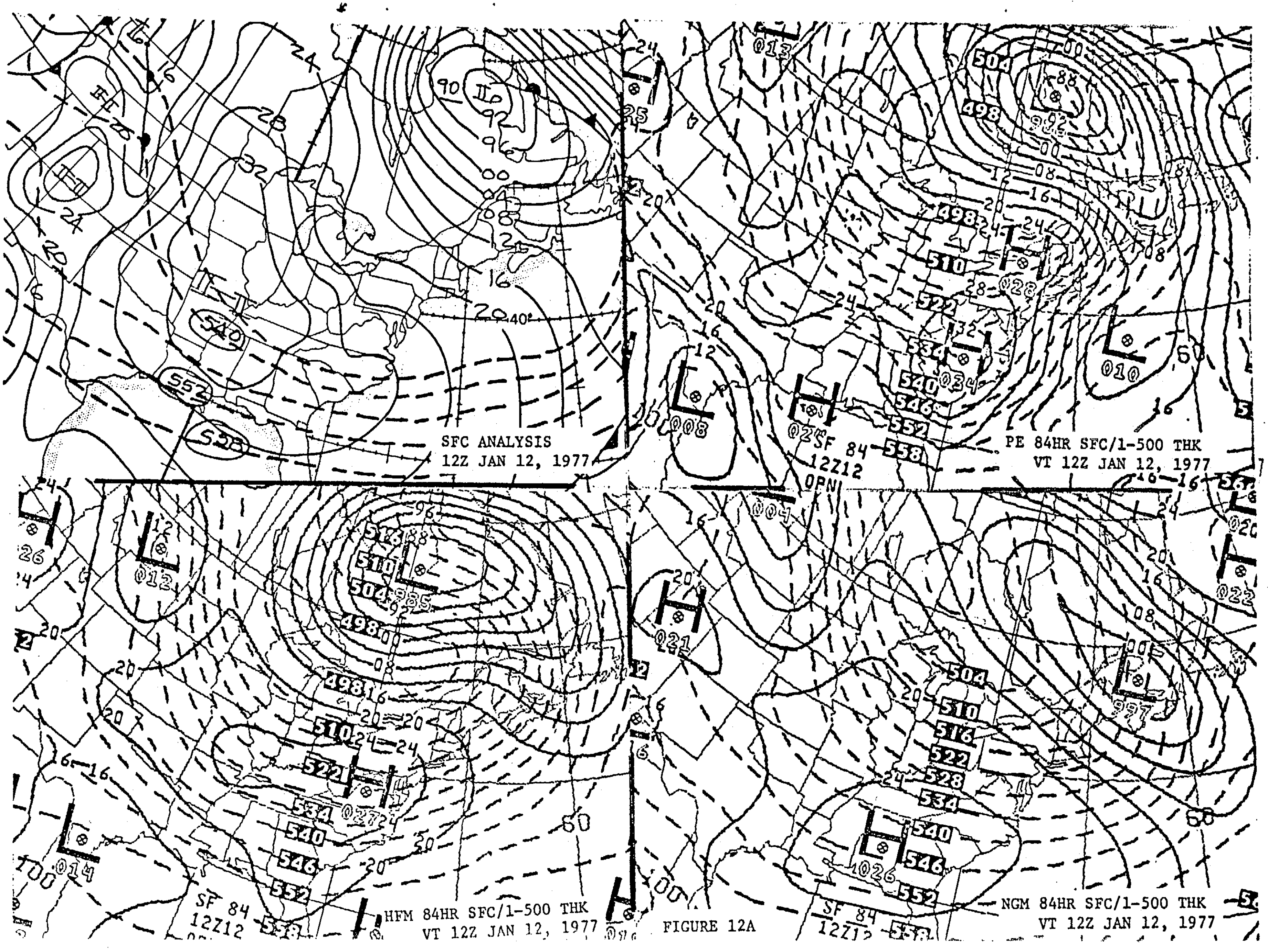
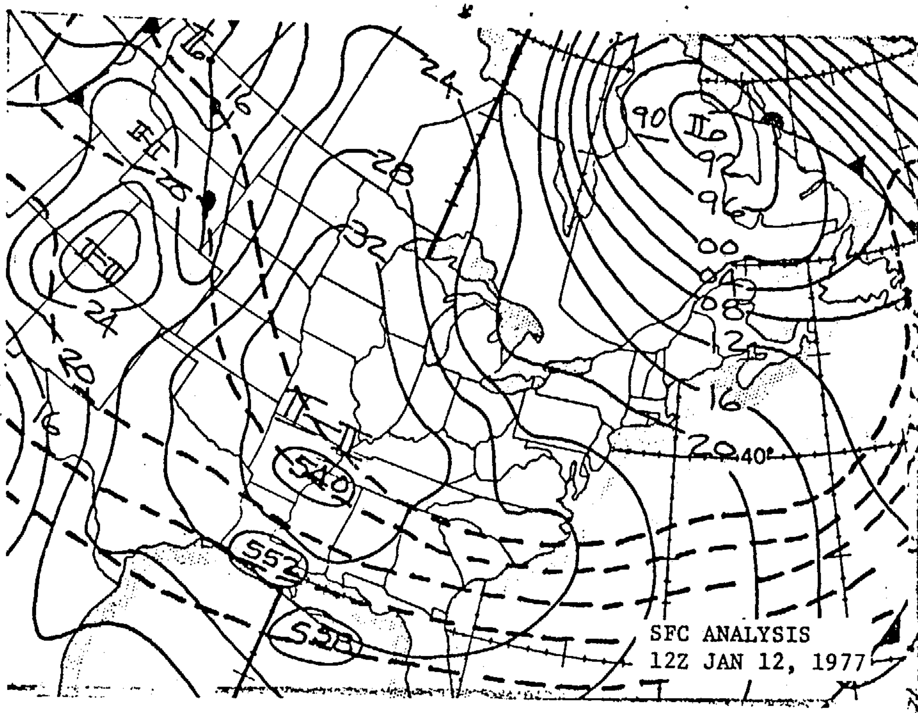
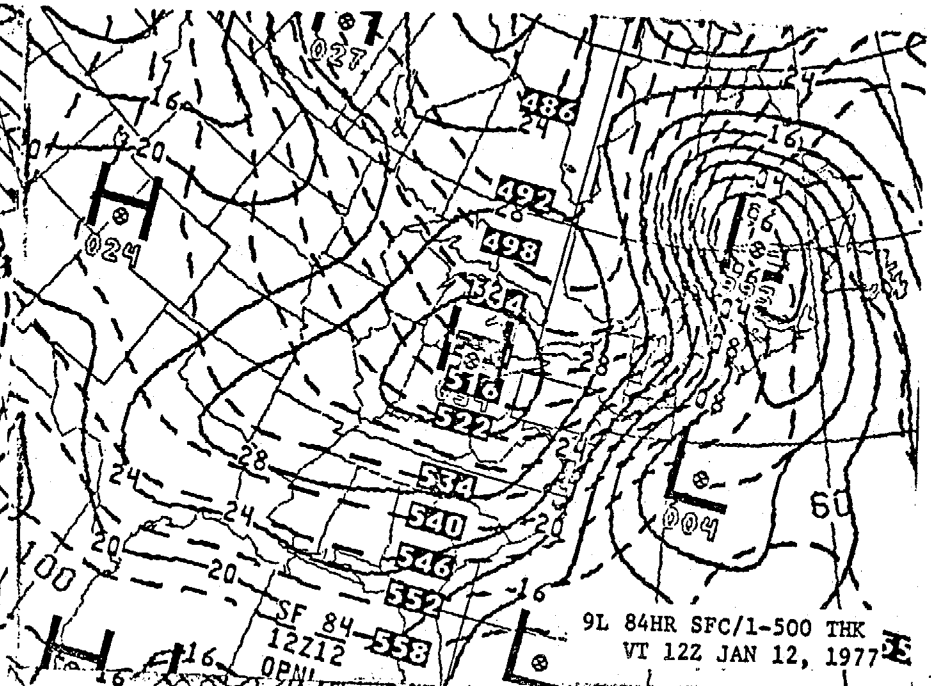

SFC ANALYSIS
12Z JAN 12, 1977
PE 84HR SFC/1-500 THK
VT 12Z JAN 12, 1977
SF 84
12Z12
OPN
HFM 84HR SFC/1-500 THK
VT 12Z JAN 12, 1977
NGM 84HR SFC/1-500 THK
VT 12Z JAN 12, 1977

FIGURE 12A



SFC ANALYSIS
12Z JAN 12, 1977



9L 84HR SFC/1-500 THK
VT 12Z JAN 12, 1977

NO 84HR LFM

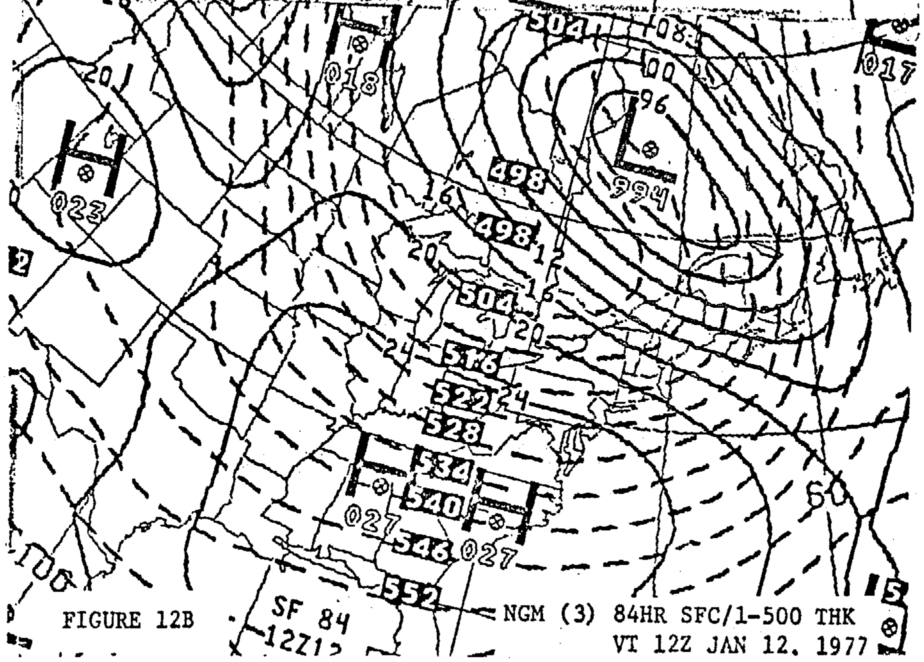


FIGURE 12B

NGM (3) 84HR SFC/1-500 THK
VT 12Z JAN 12, 1977

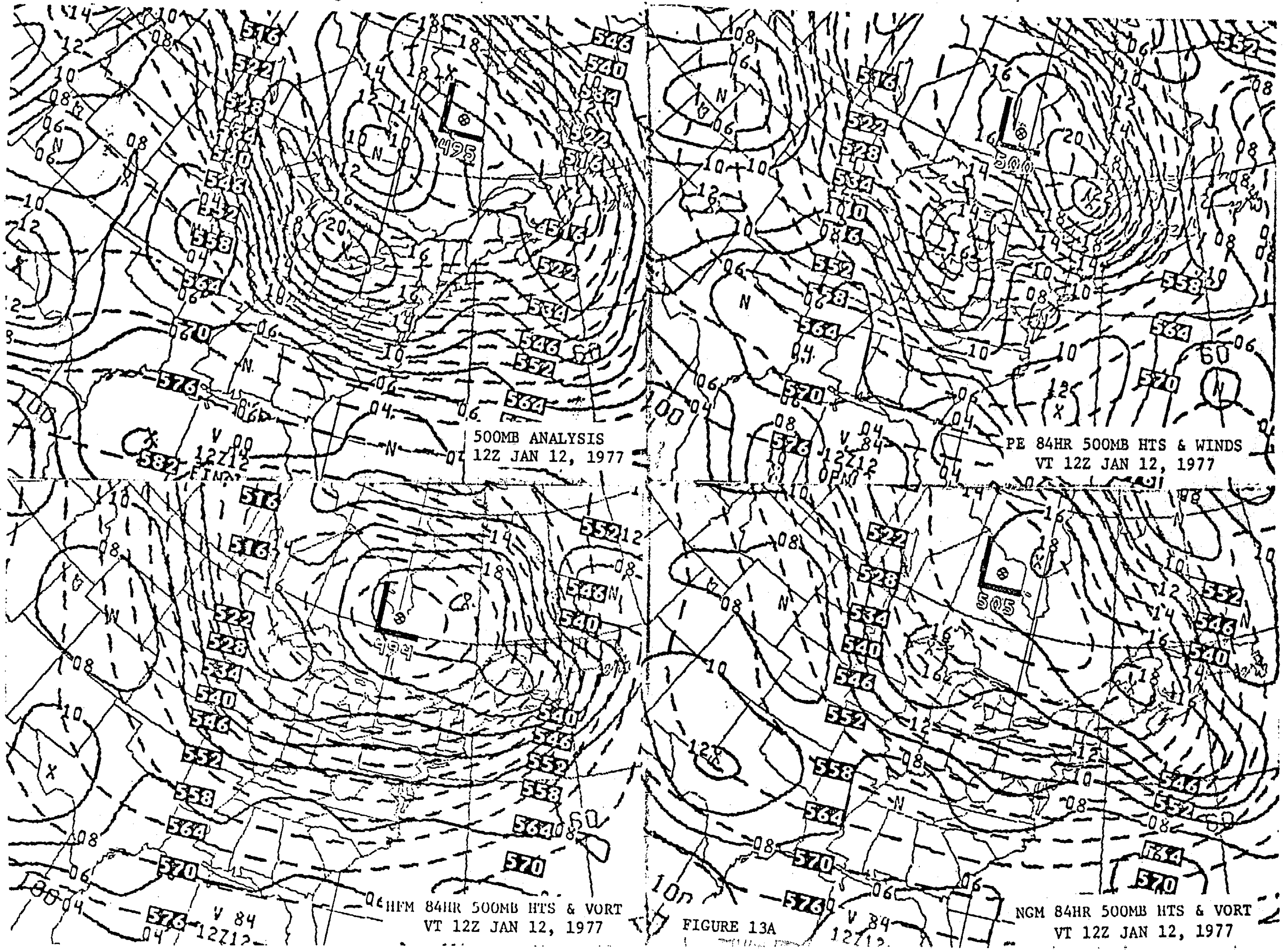
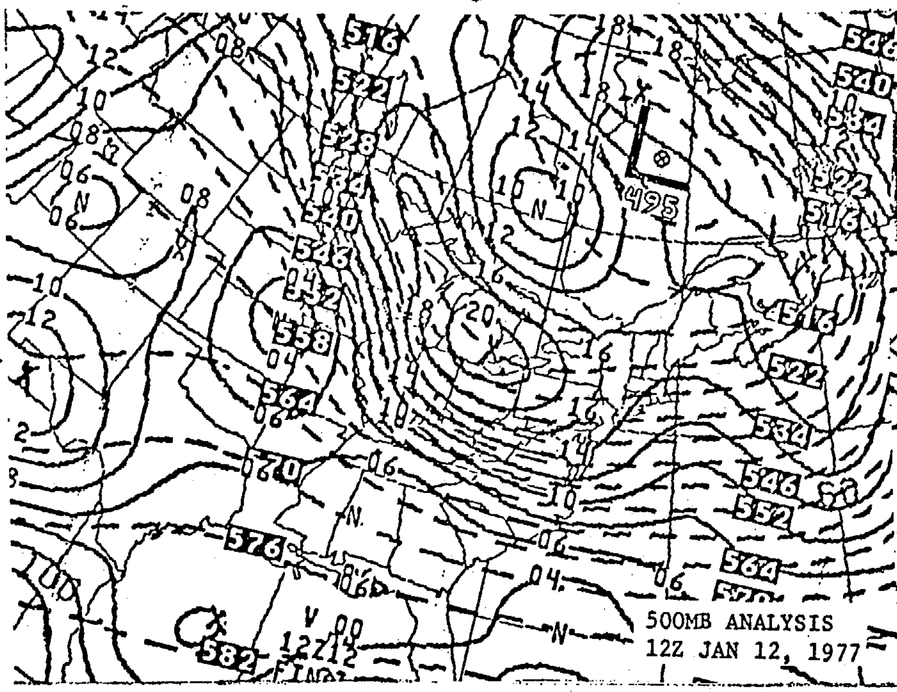
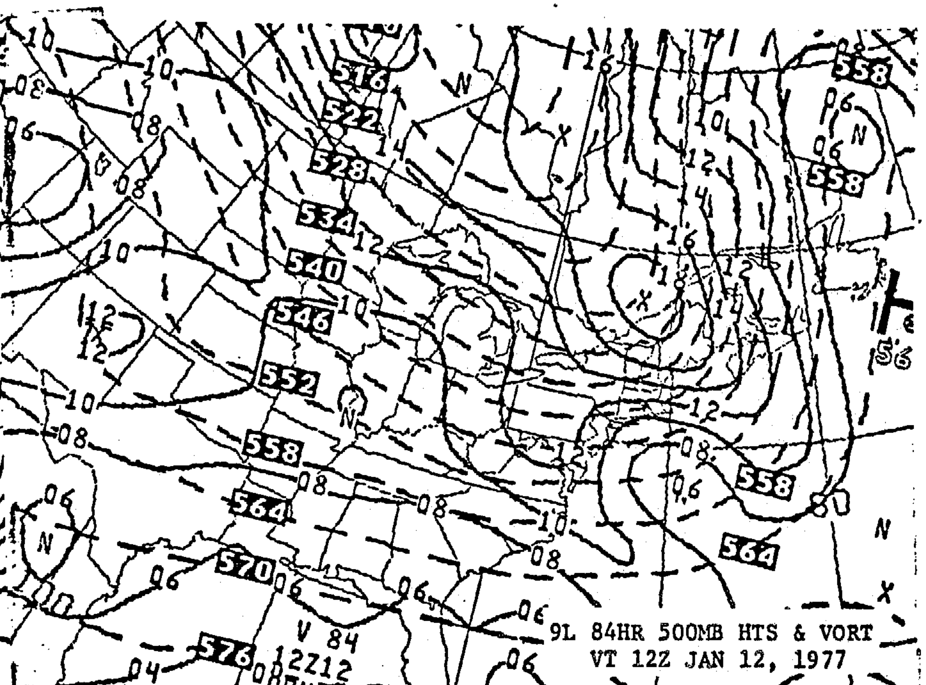

500MB ANALYSIS
12Z JAN 12, 1977
PE 84HR 500MB HTS & WINDS
VT 12Z JAN 12, 1977
HFM 84HR 500MB HTS & VORT
VT 12Z JAN 12, 1977
NGM 84HR 500MB HTS & VORT
VT 12Z JAN 12, 1977

FIGURE 13A



500MB ANALYSIS
12Z JAN 12, 1977



9L 84HR 500MB HTS & VORT
VT 12Z JAN 12, 1977

NO 84HR 500MB LFM

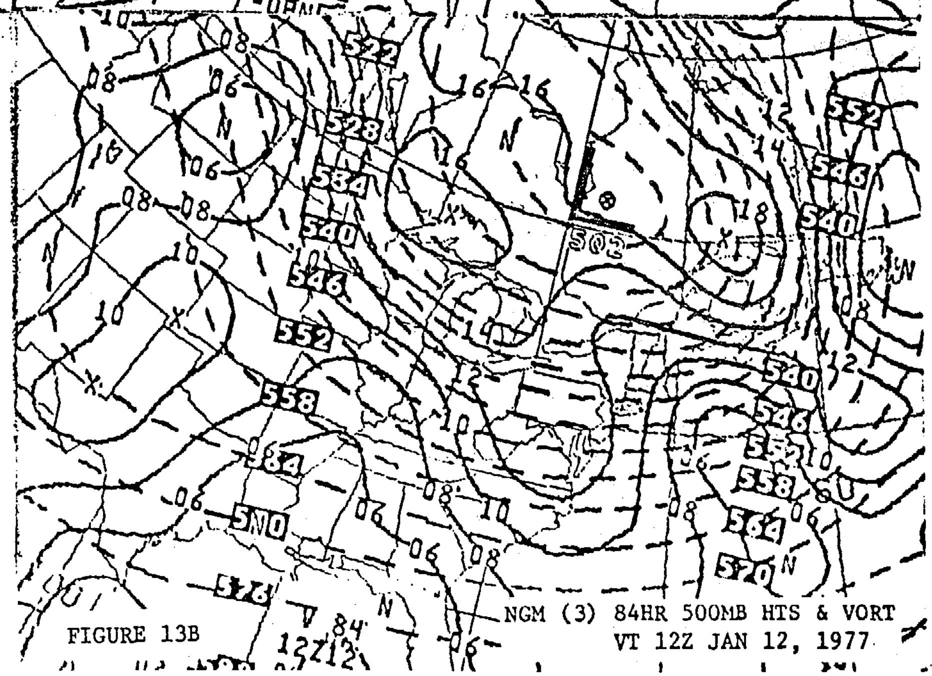


FIGURE 13B

NGM (3) 84HR 500MB HTS & VORT
VT 12Z JAN 12, 1977

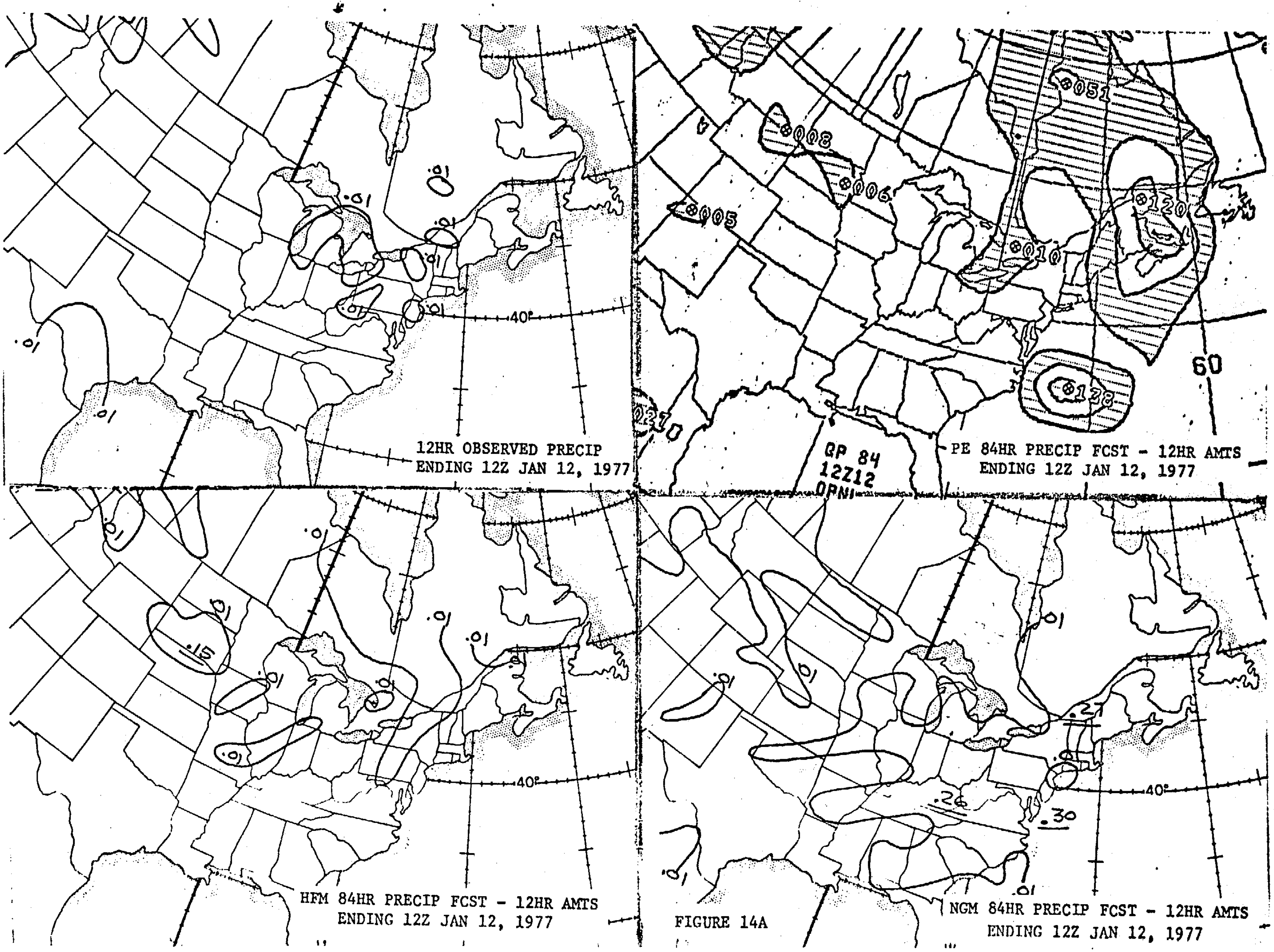
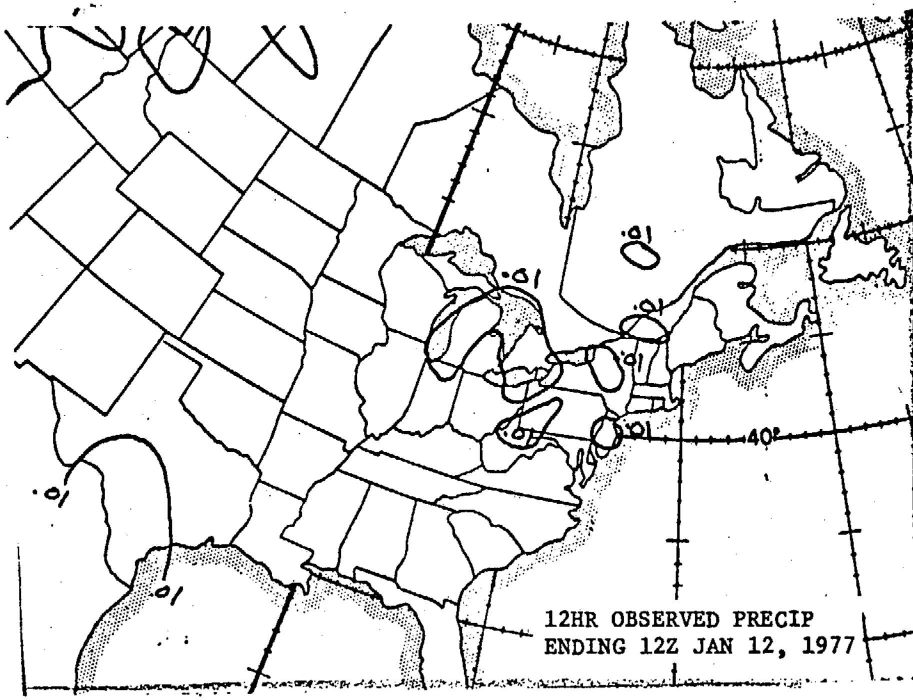
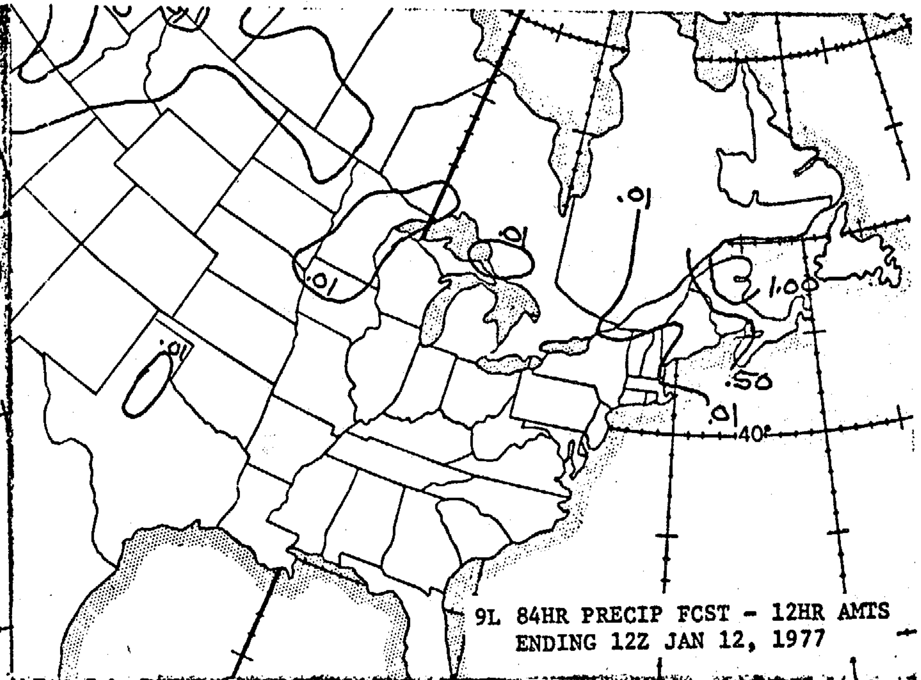

12HR OBSERVED PRECIP
ENDING 12Z JAN 12, 1977
PE 84HR PRECIP FCST - 12HR AMTS
ENDING 12Z JAN 12, 1977
QP 84
12Z12
HFM 84HR PRECIP FCST - 12HR AMTS
ENDING 12Z JAN 12, 1977
NGM 84HR PRECIP FCST - 12HR AMTS
ENDING 12Z JAN 12, 1977
40°
60
.01
.15
.21
.26
.30
051
008
006
005
010
120
138

FIGURE 14A



12HR OBSERVED PRECIP
ENDING 12Z JAN 12, 1977



9L 84HR PRECIP FCST - 12HR AMTS
ENDING 12Z JAN 12, 1977

NO 84HR LFM

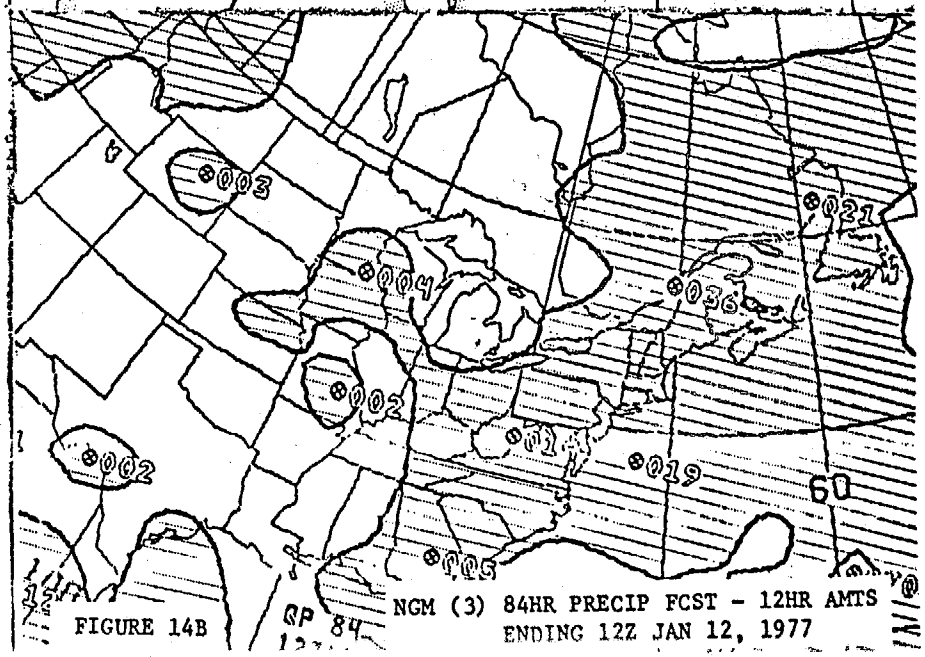


FIGURE 14B

NGM (3) 84HR PRECIP FCST - 12HR AMTS
ENDING 12Z JAN 12, 1977

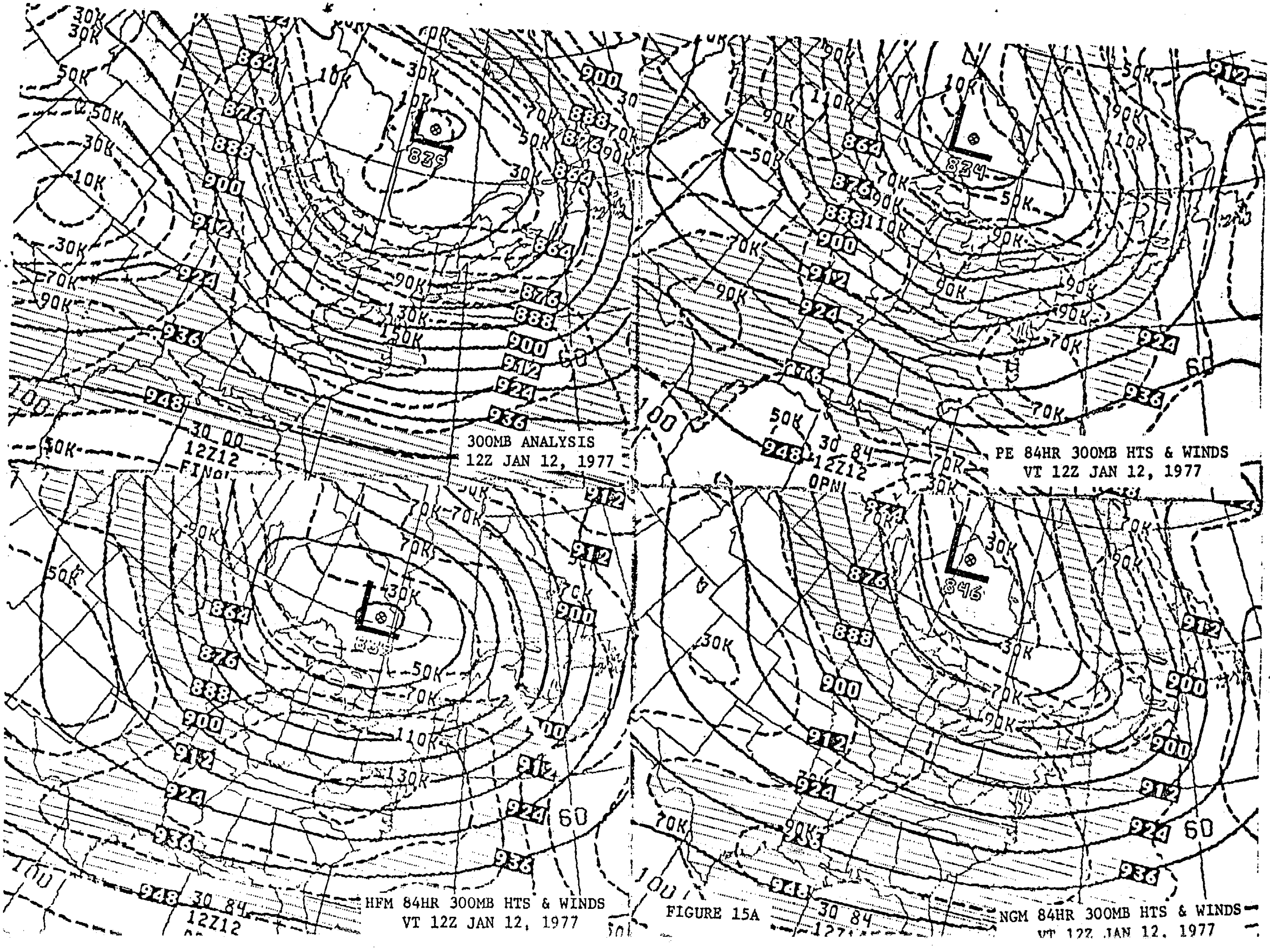
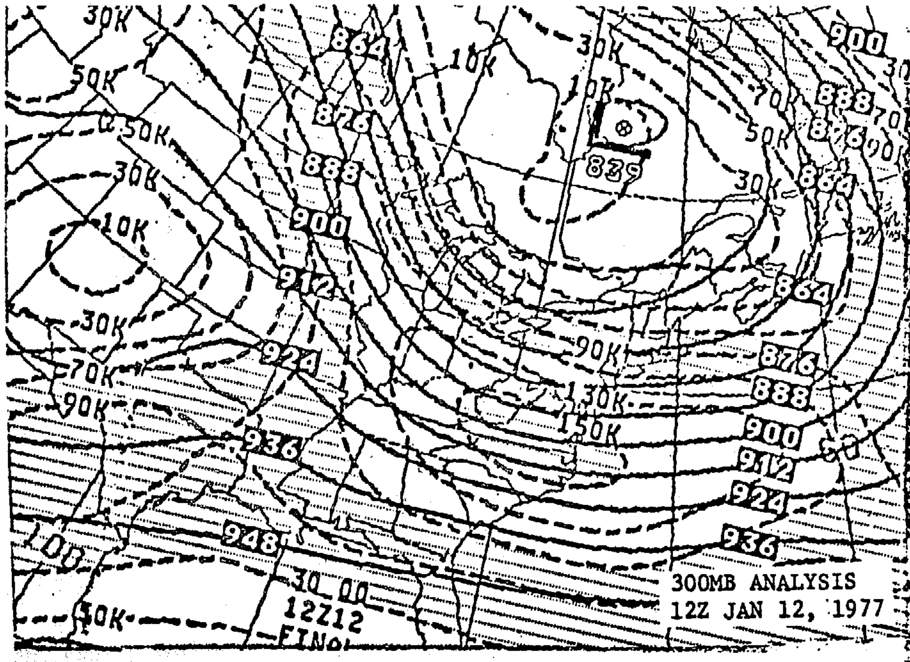
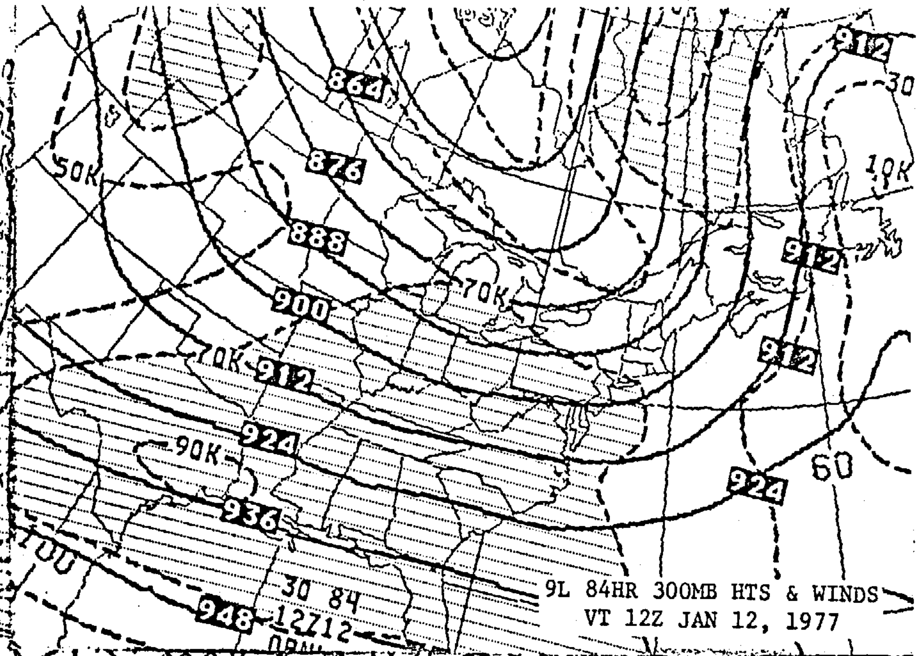

300MB ANALYSIS
12Z JAN 12, 1977
PE 84HR 300MB HTS & WINDS
VT 12Z JAN 12, 1977
HFM 84HR 300MB HTS & WINDS
VT 12Z JAN 12, 1977
NGM 84HR 300MB HTS & WINDS
VT 12Z JAN 12, 1977

FIGURE 15A

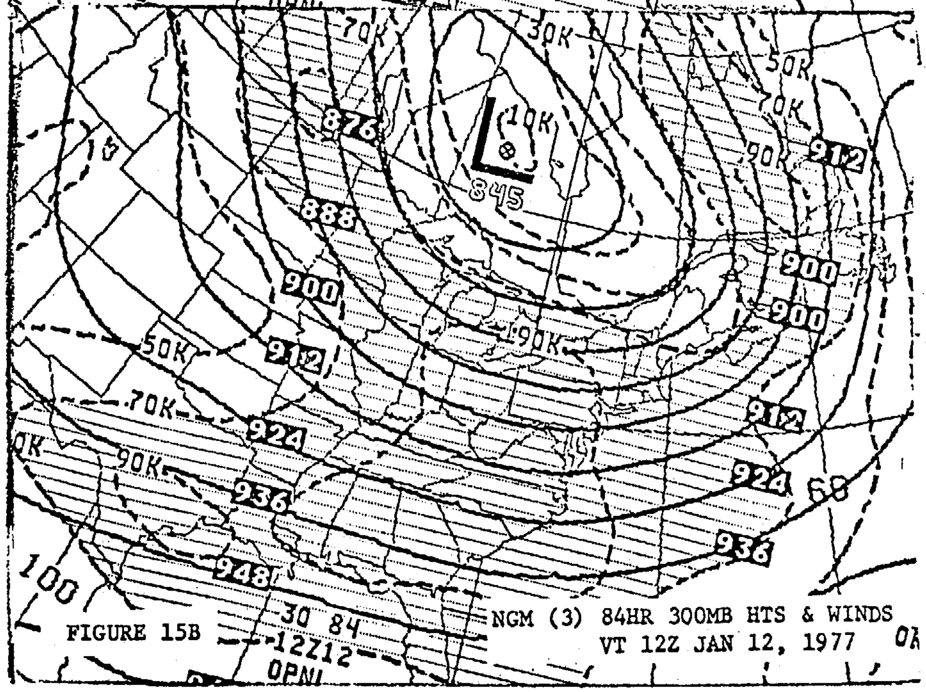


300MB ANALYSIS
12Z JAN 12, 1977



9L 84HR 300MB HTS & WINDS
VT 12Z JAN 12, 1977

NO 84HR 300MB LFM



NGM (3) 84HR 300MB HTS & WINDS
VT 12Z JAN 12, 1977

FIGURE 15B

FPI-MI 10 X 10 TO 1 INCH
5TH LINE ACCENTED, 10TH HEAVY

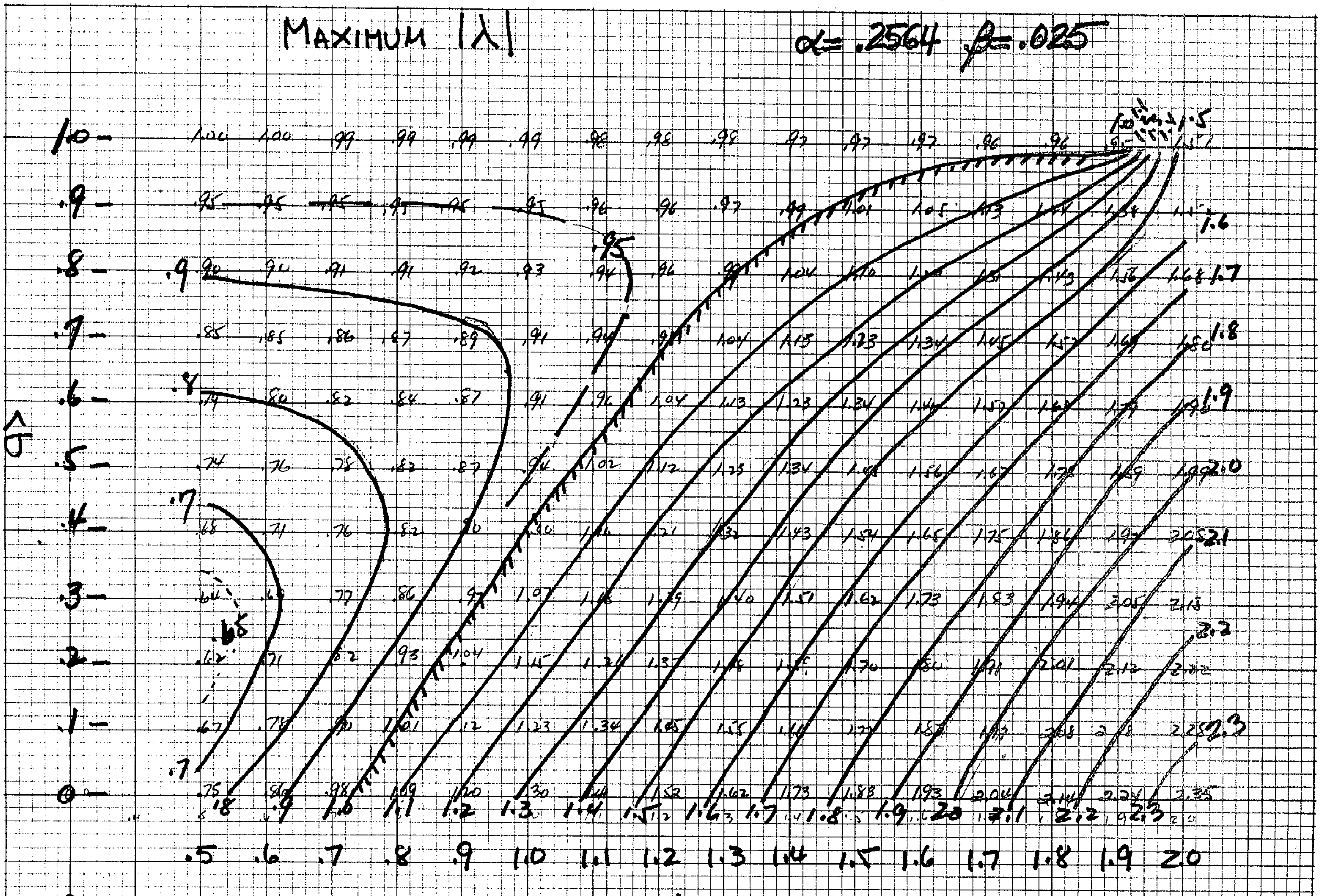


fig 1.

FPI-MI 10 X 10 TO 1 INCH
5TH LINE ACCENTED, 10TH HEAVY

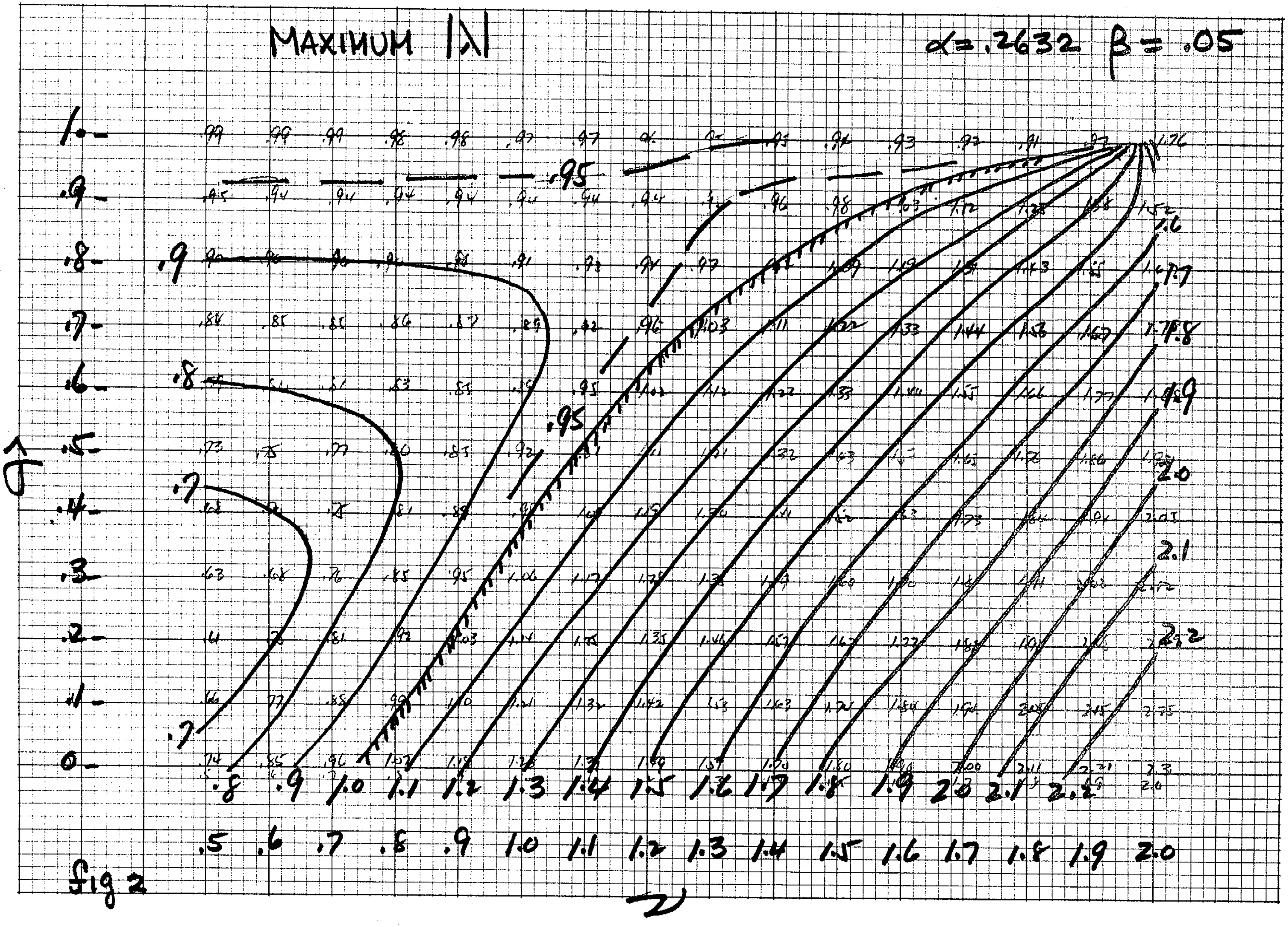


fig 2

FPI-MI--10 X 10 TO 1 INCH
5TH LINE ACCENTED, 10TH HEAVY

MAXIMUM $|\lambda|$ $\alpha = .2703,\ \beta = .0750$

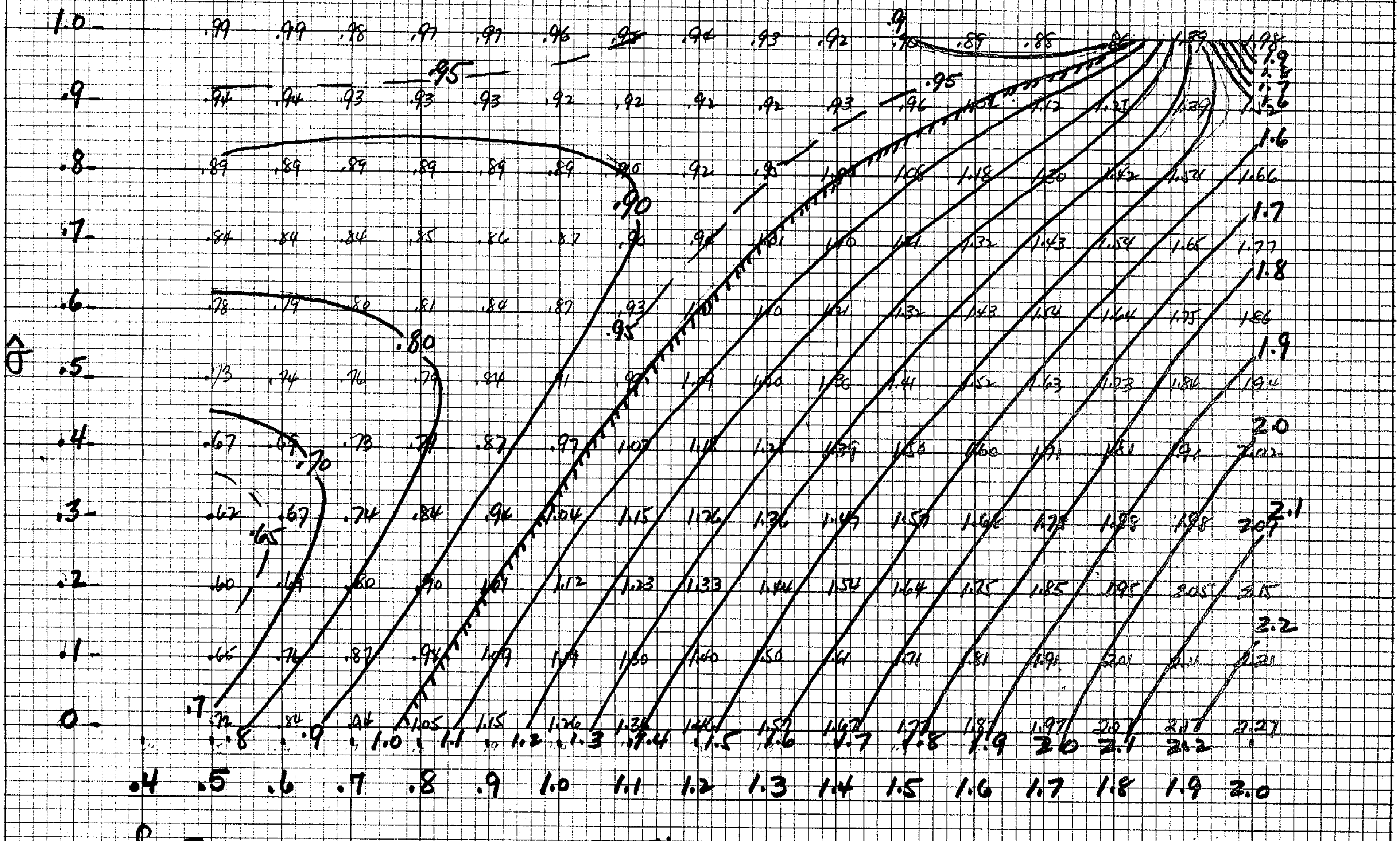
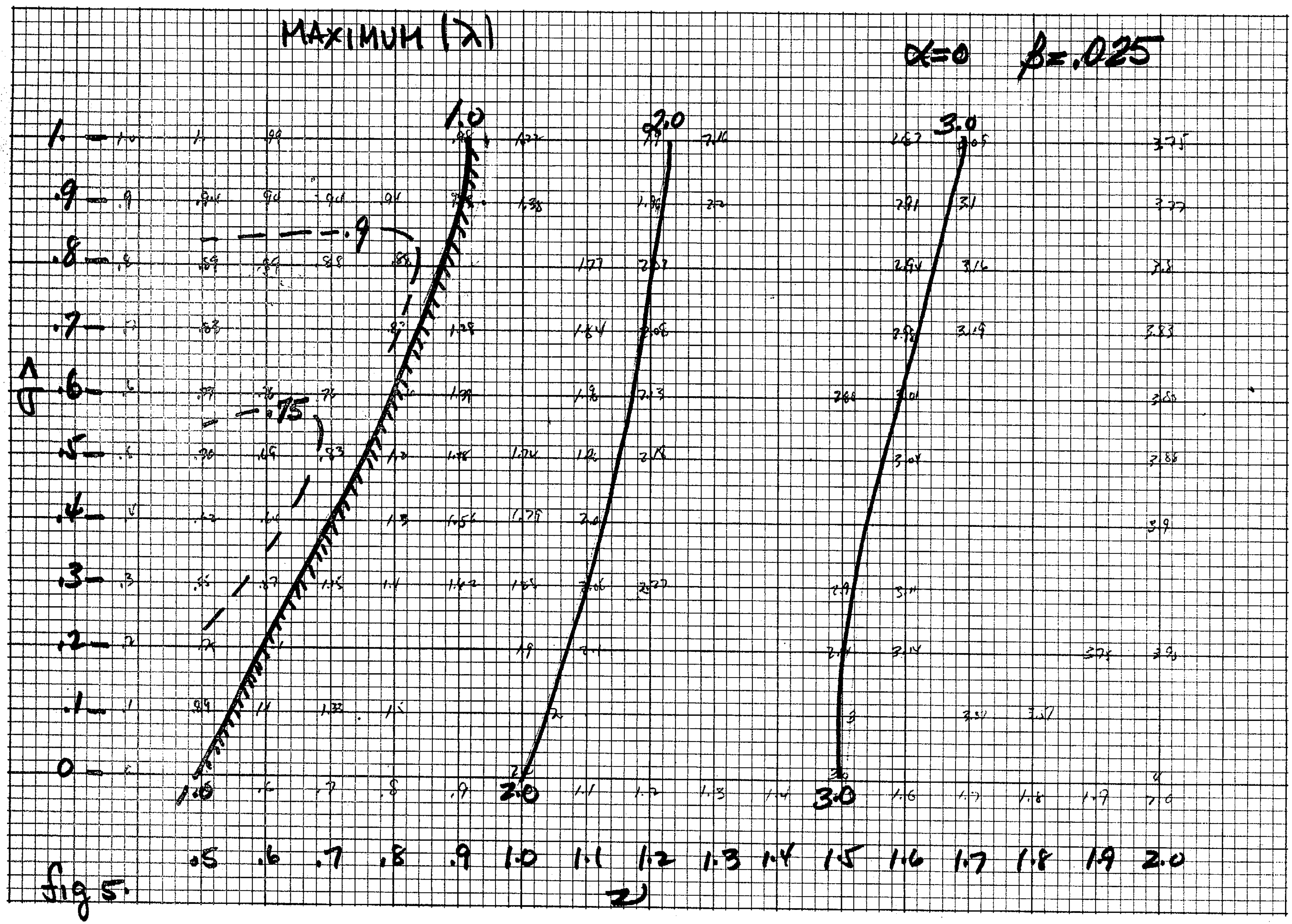


fig 3.


MAXIMUM |λ|
α=0 β=.025
1.0
2.0
3.0
.9
.75
ζ
ν
.5 .6 .7 .8 .9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0
fig 5.

MAXIMUM $|\lambda|$ $\alpha = .25$ $\beta = 0.$

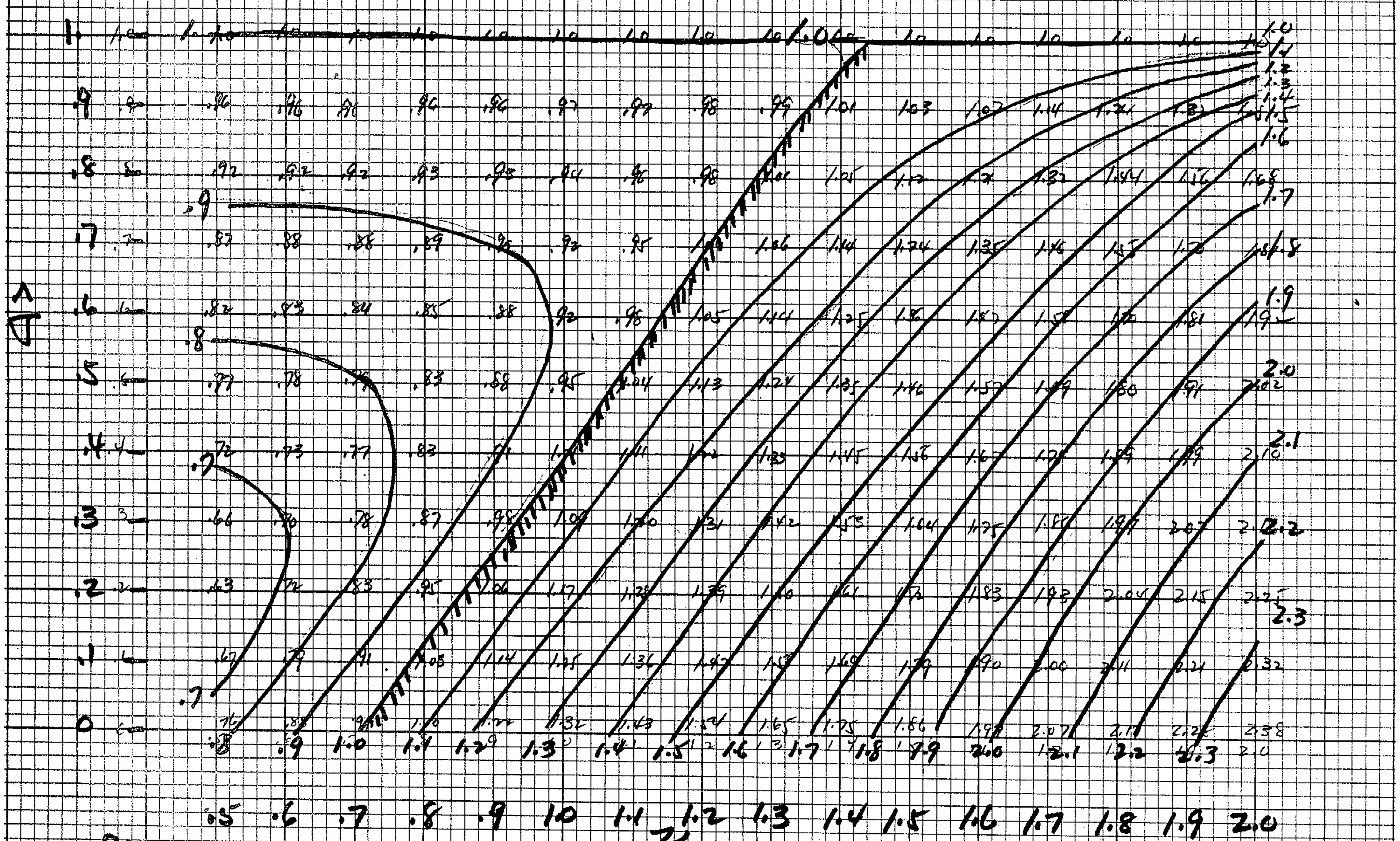


fig 4.

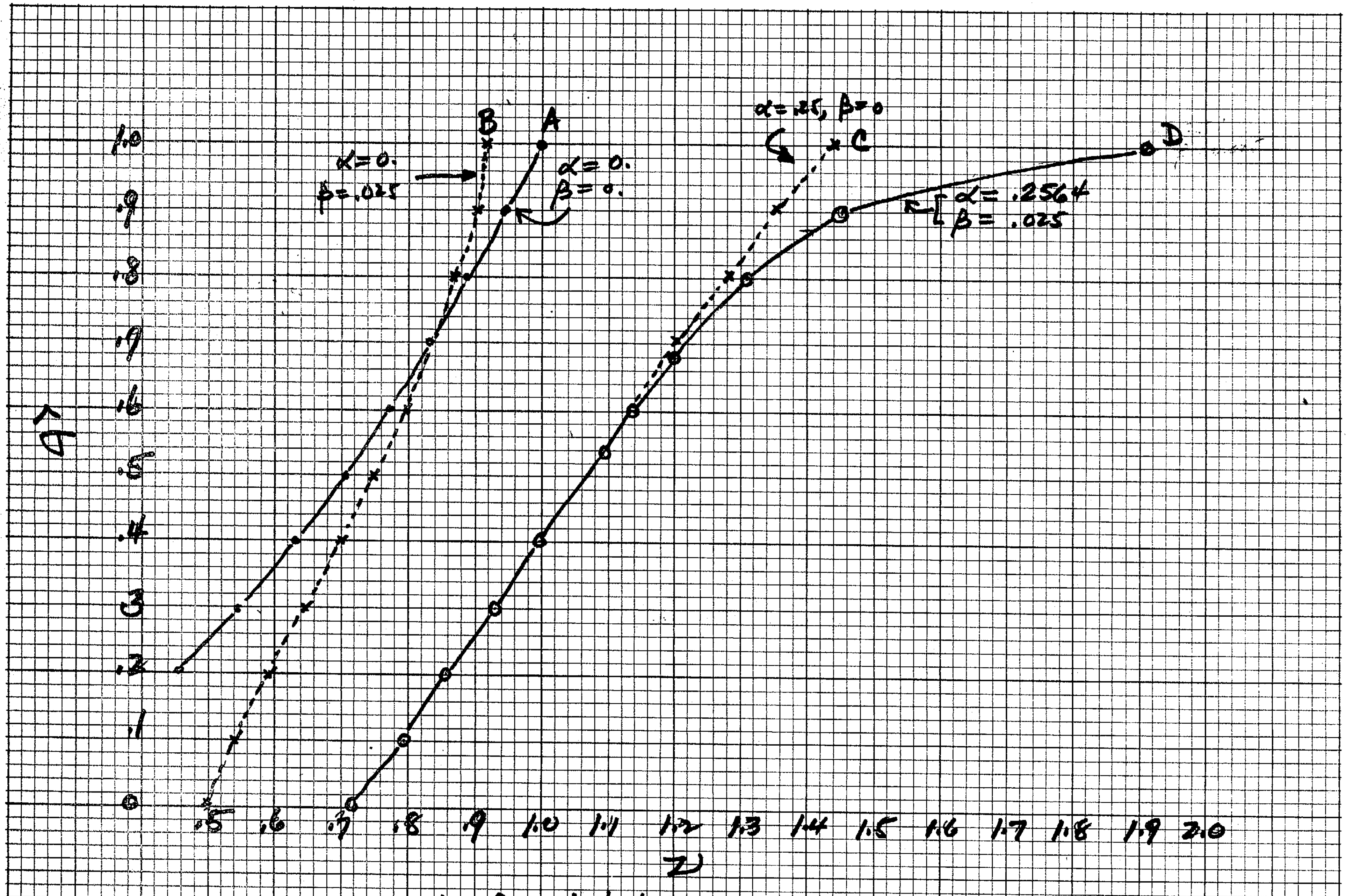


fig 6. Limit of Stability

FPI-MI--10 X 10 TO 1 INCH
5TH LINE ACCENTED, 10TH HEAVY